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AMERICAN SCIENCE SERIES—ADVANCED COURSE

GEOLOGY

BY

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Editors of the Journal of Geology

IN THREE VOLUMES

VOL. II. EARTH HISTORY

GENESIS—PALEOZOIC

SECOND EDITION, REVISED

Οὐ πολλὰ
ἀλλὰ πολύ

NEW YORK
HENRY HOLT AND COMPANY
1907

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PREFACE TO VOLUMES II AND III.

THE salient features of the purpose and plan of this work were set forth in the preface to Volume I, published two years ago. The subject of that volume, Geological Processes and their Results, is sufficiently distinct from the theme of these volumes, The History of the Earth, to give occasion for additional prefatory remarks. Though the subjects are thus measurably distinct, they have been given a common bond by the treatment of the geological processes in a historical way, on the one side, and by the development of the earth history on dynamical lines, on the other. Not only has the history been treated from a causal point of view in these volumes, but processes and principles have been discussed wherever the phase of the history has seemed to make such discussion particularly pertinent. Such special discussions have usually been introduced at the first stage in the history at which the phenomena they are intended to elucidate were declared features, or at which their expression is well suited to treatment. Sometimes, however, they have been delayed, to avoid emphasizing too many dynamic subjects at a given stage. Sometimes, too, the dynamic treatment has been divided between successive historical expressions, as when the subject is very complex, or when different phases are best expressed at different historical stages. This is the case, for example, with the dynamics of deformation, which were treated at some length in Volume I, are further discussed in the chapters on the origin and the early stages of the earth, are again touched upon in connection with several periods when deformation was pronounced, and are reverted to finally in the last chapter, in their application to the peculiar phenomena of the continental borders. A similar method is used in the treatment of climatic problems, particularly that of glaciation, which is considered at some length in connection with the remarkable Permian phenomena, because of its advantageous historical setting between antecedent and subsequent mild

periods, and is resumed in connection with the r
where localization and periodicity, together with
best expressed. This recurrent treatment is inte
some measure, the stress of treatment of these
any one point, but more especially to combine d
with the phenomena which it is to explain, as thes
themselves stage by stage. This has been done in
discussions often have their most obvious force or
and in the further belief that the definite develop
problem in its natural associations is an advar
to the discussion of the dynamic agencies that cons
It has been thought that this association of phenom
is important enough to justify even some reiterati
tions, when these are essential to firm basal conce

In harmony with this recurrent recognition o
ment in the physical evolution of the earth, sp
made to give to the evolution of the successive
inhabitants their appropriate dynamic and ph
ships. In addition to the more familiar relations
ment, the special function of the epicontinental
lations has received emphasis, because these have
through which the more legible part of the geol
made. As a corollary of this, the expansions an
land, on the one hand, and of the epicontinenta
and their contrasted influences on the life of the
low seas, respectively, have been given unusual

Special emphasis is also laid on the features
wherever the data permit. The sources of the
modes and conditions of their derivation, at all
as equally important with the sediments thems
significant of vital conditions. Base-level state
and states of much relief, on the other, are rec
factors in determining not only the character of
evolution of life on both land and sea. Terres
tinguished from marine deposits, are recogniz
particularly in the Devonian, Carboniferous, Per
chean, and Tertiary, and in the last, notably i
errestrial deposits so recognized are not mer

fluvial, in the narrower sense, but embrace also the products of general aggradation on surfaces of low gradient, by pluvial and other subaërial agencies.

On the physical side, the chief effort has been to give a connected and interpretative sketch of the earth's history, especially as exemplified by the North American continent. Imperfection of knowledge makes this sketch incomplete at some points, and limitations of space have made it brief, even when knowledge is more adequate. Both imperfection of knowledge and limitations of space have made it impracticable to deal with other continents as fully as with our own. It is believed, however, that the principles set forth in connection with the history of our own continent are applicable to all continents, and that the course of events in all has been, in principle and in leading facts, similar to that in our own.

While recognizing the alternative views, the doctrine of the permanence of the continents plays an unusually large part in the interpretations of continental evolution, of the migrations of life, and of the successive developments of provincial and cosmopolitan faunas. So also the doctrine of the periodicity of the great deformative movements forms a notable feature in the interpretations of life evolution, and in the reciprocal developments of land and sea life, as well as of provincial and cosmopolitan faunas.

Exceptional attention is given to the evolutions of faunas and floras and to their radiations and migrations, while less attention is given to the unrelated features of the life, however bizarre these may be in themselves. The familiar calling of the biological roll under each period is abandoned, and will perhaps be missed; but it has been thought that the mutations of the assemblages of composite life of the great provinces that arose in succession from changes in geographic configuration, are more important as elements in the history of the earth's inhabitants than the classification of life forms as such, particularly as such classification is still in a state of transition. The order of treatment of the various forms of life in the several periods is varied according to what is conceived to be their historical importance or natural relations.

Without giving special adhesion to any particular doctrine of life development, beyond a cordial recognition of the new mutation theor of DeVries, as well as the [illegible] and more familiar ones, the progre

evolution of life is made a subject of constant ren
tions as to biological, as well as physiographic, relatic
ence.

In the biological, as in the physical parts, the
are frankly recognized, and the student is made a
desire, if not a common effort, to secure more light
These volumes therefore attempt not merely to
facts of historical geology, and to suggest dynamic
pretations, but to indicate to rising geologists the ne
tigations, of more light, and of revised interpreta
phases of the earth's history.

Perhaps the most radical departure of this wo
dents of its class lies in the larger emphasis laid
of the origin of the earth, and especially in the int
hypothesis of earth genesis, whose dynamic seque
from familiar lines. This recognition of divergent
very outset necessarily involves an effort to carry
pretations of the whole history parallel systems o
the diverse hypotheses recognized. Especially i
try to carry out the logical sequences of the new hy
cation to the main problems that remain unsolved
of deformation, vulcanism, and atmospheric state
currently with the more familiar views, these ne
pretation form an alternative system running thro
It is believed that this will be at least stimulatin
shall prove to be a step toward the final syste
which future research alone will determine.

A few new elements of geologic classification
ally received more than partial recognition in
herein given full recognition. In the class of ti
ally designated *Eras*, the *Proterozoic*, long since
has been adopted, and made to cover about the g
the Algonkian of the U. S. Geological Survey.
made to include the group of chiefly sedimentary
systems below the Cambrian and above the gre
igneous or meta-igneous origin, referred to the Ar
Carboniferous, or Sub-carboniferous, is recogniz
tem under the name *Mississippian*, which has a

currency in America. The Lower Cretaceous is also recognized as a separate system under the name *Comanchean*. The reasons for these departures from current classification are set forth in the text. Some suggestions of further modification of the current classification are made, but not adopted, and in connection with them the criteria of classification are set forth.

Some periods have received fuller treatment than others for special reasons, usually for the sake of treating new features with some amplitude when they first present themselves in forms advantageous for exposition. The Cambrian period, for example, affords the first unmutilated record of a great sedimentary fossil-bearing system, and hence receives an elaboration that becomes unnecessary with its successors. So the Devonian period furnishes the first impressive expression of provincial life-evolution on a large scale; the Carboniferous, the first declared plant evolution; the Permian, the first well-deciphered glaciation; the Pleistocene, the immediate preparation for the human period, and so the text of these periods has been swollen by these special themes.

As in the previous volume, the endeavor has been made to keep the discussion as free from technicalities as practicable, and to render the matter readable. Certain of the more complicated problems of internal and atmospheric dynamics render this well-nigh unattainable, as frankly confessed by the relegation of certain portions to small type. The description of the many complexities of the geographic distribution and of the composition of the various formations cannot be wholly freed from tediousness to the general reader; but they are so essentially serviceable for local and special studies, and even for a concrete general conception of the variety of concurrent geological processes, that their admission is regarded as indispensable.

The three volumes are designed to furnish the basis for a year's work in the last part of the college course, or in the early part of a graduate course. It may seem at first thought that the amount of matter is rather large for this, but the educational saw, that, in things historic, nineteen pages of flesh-and-blood are an easier assignment than nine pages of bare-bones, is believed to have an application to geologic history. By judicious selection of material to be presented and omitted, the volumes will be found useful for briefer courses, an by the use of the num [illegible] eferences to the discussions of s

treatises, they may be made the basis for much more
than are commonly given in undergraduate work.
hoped, be of service as reference books where short
given.

No attempt has been made to make these volum
the details of the geology of individual regions will
them, except as these details have been thought neces
pretation of the general phases of the subject. For l
and National Survey reports, and other special mon
consulted.

In the account of the geology of each period, the t
that the physical history of the continent may be
consecutively, without especial reference to the hi
and conversely, so that the history of life may be
as an independent, unified subject. This is an adap
venience of those institutions whose division of i
permits a separation of the treatment of the physi
logical phases of the subject.

Acknowledgments, in addition to those made
due to many colleagues who have rendered valuable
ration of these volumes. In the portions relatin
paleontology, the assistance of Dr. Stuart Weller
erous and unreserved that he has been scarcely less t
Almost as much may be said of the assistance of Dr
and E. C. Case in the portions relating to verteb
and of Drs. J. M. Coulter and H. C. Cowles in paleob
tion of the invertebrate illustrations and the prepar
tated legends have been largely the work of Prof
many of the figures for these illustrations have bee
work under his supervision by Miss Mildred Mar
read both the manuscript and the proof. Dr. Will
manuscript and proof of the portions relating to v
the cosmological portions, the collaboration of Dr.
has been of indispensable service. In certain m
lems, Dr. A. C. Lunn has given valuable advice,
Stieglitz has done the same in connection with
The colored map of the American formations has
essor Bailey Willis. The series of analytical m

periods were compiled and drawn by Mr. C. E. Siebenthal under the supervision of the authors. Many of the figures in the text were drawn by Mr. G. A. Johnson. In other ways, much valued aid has been rendered by Professors E. B. Frost, A. A. Michelson, C. R. Barnes, J. P. Goode, H. G. Gale, and Messrs. Edson S. Bastin and Eugene W. Shaw. Various individual investigators, publishers, and surveys, preëminently the U. S. Geological Survey, have furnished material for illustrations. In general these contributions are acknowledged in the text.

The references to Volume I are to the second edition, in which the pagination numbers are higher than those of the first edition by a little more than one in twenty, as a rule.

UNIVERSITY OF CHICAGO, December, 1905.

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GEOLOGICAL MAP OF THE UNITED STATES AND PART

GEOLOGY

VOL. II

GEOLOGY

CHAPTER I.

THE ORIGIN OF THE EARTH.

THE strata of the earth reveal its history with great fidelity for long periods previous to the present, but earlier than that the record becomes indistinct, and if we attempt to follow it back to the beginning, the indistinctness merges into extreme obscurity. The rocks at the base of the known sedimentary series are so greatly disrupted, crumpled, crushed, metamorphosed, and traversed by intrusions, that their history is deciphered with the greatest difficulty and no little uncertainty, while below these lies the inaccessible interior of the earth whose formation constituted a still earlier chapter in the history. The nature of this inaccessible mass can only be inferred from volcanic extrusions, the transmission of seismic tremors, the phenomena of gravity, the distribution of rigidity and of internal heat, the modes and processes of deformation, and other phenomena of a more or less dynamic kind. All these phenomena have their bearing on the problem of the earth's origin, but just what they imply cannot yet be interpreted without some measure of reasonable doubt.

Besides these internal phenomena, suggestions relative to the origin of the earth are to be found in its characteristics as a planet, and in its relations to the other members of the solar system. Suggestions are also to be found in certain features of the solar system which show that it had no haphazard origin. The birth of the system is beyond doubt revealed in its constitution and in its dynamics, if one could but read the record. But all these phenomena of external relations, as of the hidden interior, are difficult to interpret, and the meaning they carry cannot be read as we read the sedimentary record. We do read dynamical records. In the fall of rain we readily read the previous ascent of vapor, not so much by any material record as through a known system of atmospheric dyna follow the growth of an oak back to its origin by re processes. By three observations of the apparent comet, the astronomer traces its path both backw In a somewhat similar way, the history of the eart time be traced to its beginning through its dynami is quite certain that the earth and the solar system pursuance of a definite succession of progressive virtually recorded in the phenomena of the prese fuller and deeper insight into such phenomena is a will doubtless become quite readable, and the int

While awaiting this, we must be content with these are our only resource, there is need to form a as possible of those hypotheses that have been or n and of their working qualities as applied to the pro It is not less important to acquire at the same tim intelligent preparedness to appreciate new light itself.

Not a few of the doctrines of geology, when t ultimate terms, are found to hang on some hypot initial stage, and to have no greater strength th It is therefore important to scrutinize these basal critically the ways in which they enter into the i earth's phenomena, and into the various geologic carry into the study of earth-history a never-fai hypothetical dependencies. This should serve as against the acceptance of conclusions as substanti in reality hypothetical in their ultimate dependen it guard against the *unconscious* acceptance of co they were demonstrated, when in reality, traced a st they may be found to be grounded solely on a h

It is the glory of geology that it is a growin has an enormous mass of the firmest data, and i rest on most substantial grounds and will never b by any developments in the future, it has, at th problems that are yet unsolved, many doctrines th y depths that are yet unfathomed. At all s an investigative spirit: it courts an attit thought and of critical scrutiny. Especially is this true of the hypotheses of the origin and early states of the earth, to which we now turn.

HYPOTHESES OF THE EARTH'S ORIGIN.

It is the nearly unanimous conviction of astronomers that the solar system was evolved in *some* way from a nebula of *some* form. Until recent years, the majority of astronomers accepted the special theory of Laplace, presently to be sketched. So general has been this acceptance that the theory of Laplace has come to be known as "The Nebular Hypothesis," and when this phrase is used without qualification, this particular hypothesis is usually meant. The advance of inquiry, however, makes it necessary now to consider at least two other hypotheses, each of which postulates that the solar system arose from a nebula, but a nebula whose constitution and mode of evolution differed from that postulated by Laplace. In a broad sense, all these are nebular hypotheses. Each of them embraces sub-hypotheses or variations, but in their basal features they are distinct and form three definite classes.

I. **The gaseous hypothesis.**—In this, the parent nebula is assumed to have been formed of gas aggregated by gravity in accordance with the laws of gases, and to have been evolved into the present state by a gradual passage from the original system of gaseous dynamics into the present system of planetary dynamics. The type of the class is the Laplacian hypothesis.

II. **The meteoritic hypothesis.**—In this, the parent nebula is assumed to have been a swarm of meteorites, the individual members of which moved in diverse directions and suffered frequent collisions, attended by heat, light, and vaporization. The type is the conception worked out by G. H. Darwin, in which the swarm of meteorites is thought to have behaved essentially as a coarse gas, the evolution of the system being dynamically like that of a gaseous system: indeed, the initial meteoritic aggregation may have actually passed, at a later stage, into a gaseous one by the vaporization of the constituent meteorites.

III. **The planetesimal hypothesis.**—In this, the constituents may be molecules or small masses of any kind moving in orbits about common center. They are not primarily controlled by collision rebound as in the pre[illegible] cases, but by revolution about the

mon center of gravity or some central body, as are t
In other words the constituents are infinitesimal plane
mals. Under this hypothesis the dynamical system w
same at the outset as it is now; the evolution has
aggregation of the planetesimals into planets and sat
ally considered, it differs more from the other two hy
do from one another, but it is liable to be confused
from which, however, it departs fundamentally. Th
ses will be considered in detail.

I. THE LAPLACIAN OR "NEBULAR" HYPO

During the last century the Laplacian hypoth
of the solar system was almost universally accepted
and geological theories respecting the early states
respecting many of its subsequent events were built
views remain largely prevalent to-day.

The postulated nebula.—The Laplacian hypoth
the matter of the solar system was once in an extr
ous condition and formed a vast spheroid extending
most planet and rotating in the same direction as t
How this condition of things arose was not defini
Laplace. It has since been referred to the collision c
and to other agencies. The extreme tenuity of th
thus postulated is to be noted, for computation
density but a small fraction of a millionth of the de
phere at the surface of the earth, while its outer
much less.[2] The hypothesis assumes that this
rarefaction was maintained by intense heat.

Formation of rings.—The hypothesis holds tha
of this heat by radiation must have resulted in con

---

[1] A somewhat similar hypothesis was advanced earlier by
and a cruder one still earlier by Thomas Wright. Swedenbo
tion in the same line. These earlier attempts, however, comn
and the wide acceptance which the hypothesis gained later
elegant elaboration given it by the mathematical genius of La
influence of his name which it properly bears. The hypothe
the slightly modified forms usually held at present.

[2] Kelvin gives the average density of a gaseous nebula hav
f the earth's orbit, as 1/570,000,000 of that of common
of 10° C. (Pop. Lect. and Add. I, p. 419). F. R. Mo
when the nebula extended to the orbit of Neptune, 1,

this must have led to accelerated rotation. When the rotation reached a certain speed, the centrifugal acceleration at the equator of the spheroid would come to equal the centripetal acceleration of gravity. The equatorial portion would then no longer contract, while the remainder, having less rotational speed and continuing to shrink from further loss of heat, would draw away from it. The equatorial portion is commonly said inaccurately to be "thrown off." The hypothesis assumes that the equatorial matter so left behind would constitute a ring resembling the rings of Saturn; indeed, there is little doubt that the Saturnian rings suggested the theory. It further assumes that, as the cooling and contraction of the spheroid continued, additional rings to the number of the present planets were left behind.

It has been objected that the matter left behind in this way would separate particle by particle, forming a kind of disk, and not a series of definite rings, since the centrifugal acceleration would come into equality with the centripetal gradually and at different times for each successive distance from the center. There could have been no appreciable cohesion to restrain the separation; on the contrary, the individual velocities of the molecules should have aided individual separation. But this is not the view taken by the hypothesis.

Formation of gaseous spheroids.—It is further assumed that as the rings cooled they parted at their weakest points and collected into spheroids which were still hot and gaseous like the original spheroid. These afterwards followed a similar course of evolution, detaching rings in most cases, which in turn parted and gathered into smaller spheroids.

The spheroids into which the first set of rings contracted are assumed to have at length condensed into the several planets, those of the secondary rings into the satellites, while the great central spheroid formed the sun.

The earth-moon ring.—In the case of our planet, it is held that the matter of the earth and moon together was originally separated from the solar spheroid as a common ring at a rather late stage in the evolution of rings, and that this ring coalesced into a hot gaseous spheroid which, in the course of its contraction, in turn detached a ring from its equator, and that this ring condensed into the moon.

air at the earth's surface (Tests of the Nebular Hypothesis, Astrophys. Jour., Vol. II, 1890, p. 114).

According to the original Laplacian hypothesis, the separation of the moon-ring,.was still a spheroid continued to cool and shrink until finally its main a liquid and at length into its present state.

Darwin's modification.—George H. Darwin[1] has fication of the theory, so far as relates to the moon, to have separated, not as a ring while the earth w panded gaseous condition, but as a lump, or as a se after the earth had concentrated to a liquid or perhaps solid state. By a beautiful mathematical investigat of a postulated body-tide of the earth upon the moti he concluded that the moon has been forced to retir a position at or near the earth, to its present distan of its history. The tidal protuberance of the earth by rotation, and so tends to draw the moon forward in causes the moon to take a larger orbit, while the the moon on the tidal protuberance tends to retar the earth. That the tides tend to force the moon measure, is a sure deduction from the dynamics of the assumption of a body-tide, and hence it seems moon was originally nearer the earth than it is no nearer remains an open question on which we have On account of its close relations to the earth, the of the moon are matters of great interest, but the di have been entertained cannot be pursued into detail

Supposed passage of the earth from the gaseous t dition.—The Laplacian hypothesis assumes that remained essentially in the gaseous condition unti central portion fell to the temperature of liquefac refractory matter, when a liquid nucleus formed. on, this grew until the chief rock-substances had co molten globe, while the more volatile material rema state and formed a vast hot atmosphere.

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[1] On the Secular Changes in the Elements of the Orbit of a Sat a Tidally-distorted Planet, Phil. Trans. Roy. Soc., Pt. II, 188 Friction of a Planet Attended by several Satellites and on the ditto, Pt. II, 1881.

I, p. 576.

The supposed crust.—It was formerly held that the next step was the crusting-over of this molten globe by surface cooling, and that this was followed by a progressive thickening of the crust. It was a common view that this state continued even down to the present day, and that the earth still consists of a liquid interior inclosed in a solid shell. The term "crust of the earth" arose from this belief, and it is still much used as the most convenient term for the outer part of the earth, even by those who do not attach the original meaning to it. Against this view it has been urged that solid lava is heavier than molten lava and should therefore sink to the center as fast as it formed. In reply it is urged that, in such a molten globe, the heaviest material would gather at the center, with successive layers of lighter and lighter material above it, the lightest of all being at the surface, so that, even though the solidified portions of this lightest layer were heavier than their own liquid stratum, and so would sink through it, they would still be lighter than the heavier liquid layers below, and would thus be arrested by them. These sunken portions might be remelted for a time, but the process would at length so cool the whole outer layer that remelting would cease, and a subcrust would form which, in time, would be built up to the surface and give a complete crust formed of the outermost layer of light material. In pursuance of this view, it was supposed that the granitic group, the lightest class of igneous rocks, formed the primitive surface, but this special view has been weakened by recent studies of the oldest known rocks.

Astronomical argument for solidity.—Arguments against a crust resting on a liquid bed have been brought to bear by physicists and astronomers who, reasoning from the phenomena of the tides, of the precession of the equinoxes, of variation of latitude and of nutation, have urged that the earth must be essentially solid; must, indeed, have a practical rigidity of a high order. The support of the continental platforms at a height of 12,000 to 18,000 feet above the ocean basins, as well as the support of the great plateaus and mountain ranges superposed on these, present other grave objections to the hypothesis of a liquid interior. To these last objections, the answer has been made that the continents, plateaus, and mountains are inherently lighter than the material of the ocean bottoms, and this seems to be essentially true To the astronomical argument it has been replied, in part, tha [illegible] ff liquid inclosed in a thick shell and rot

ting rapidly would act toward a transient extern
it were a solid.

Notwithstanding these answers, the opposing
greatly reduced the number of adherents of a mol
whom were once embraced the great body of geolo
still held, however, by eminent geologists, and—wh
to note—it remains embodied *unwittingly* in man
to the interior and to its dynamics which are held
ceased to hold the parent view. A striking exam
in the thermal discussions of Lord Kelvin and oth
form temperature in the deep interior is assume
corollary of the conception of surface cooling a
apparently can have no other basis. Yet it has
into nearly all the fundamental doctrines of defo
ings have been indicated in Vol. I, pp. 559, 560.

Supposed solidification from the center outwa
which shrink in solidifying, as do most rocks, it is
the melting-points are raised by pressure. Out
the doctrine that solidification due to pressure woul
of the earth while yet the outer part was liquid.
much strengthened by the experiments of Barus
such pressure as could be applied, Barus found the
point of a typical rock (diabase) to be directly as the
by computation to the center of the earth, the
be 76,000° C. It is of course uncertain whether
good throughout the extraordinary conditions o
and little weight is to be attached to the precise
general deduction is of fundamental importance
of solidification under pressure, in spite of heat,
support of the best available experimental data,
astronomical and topographic arguments for a soli
to have wide acceptance. Under this general vie
that the solidification continued outward from
surface was reached, and that the surface cooled la
precisely the opposite of the old view.

Supposed middle molten zone.—By others it is
over at the surface took place before the

U. S. Geol. Surv., Bull. 103. See also Vol. I, this reached the surface, and that there was then a zone of liquid between a solid crust and a solid center. This zone is thought by some to have remained to the present time; by others to have solidified later, and by still others to have partially solidified so that the crust is joined to the central mass by solid supports, while residues of liquid have been left between in certain portions. By postulating these liquid residues, a source for the lavas ejected at later stages is hypothetically provided.

Hypothetical gaseous center.—Against the view of a solid center it is urged that the temperature of the gaseous globe at its center must have been above the critical point, and must have risen with progressive condensation so long as it remained in the gaseous state, and hence that the gaseous center could not have taken on the solid state. A globe with a gaseous center is therefore a fourth conception. How this is to be reconciled with the evidences of rigidity and other physical phenomena of the globe is not obvious.

There thus arise from the Laplacian hypothesis four general conceptions of the state of the body of the earth: (1) that it is all liquid within and merely crusted over, (2) that it is solid at the center and crusted over on the surface, with a liquid or partially liquid zone between, (3) that it is solid throughout, and (4) that its center is gaseous and its exterior solid.

Part played in geologic doctrines.—The view that the earth was once in a molten state very naturally led to certain inferences as to the internal arrangement of the matter, the original form of the surface, the state of the primitive atmosphere, and to a long chain of dependent interpretations; and so the hypothesis has become interwoven with the interpretations of nearly all the great phenomena of geology. The changes in the form of the earth, the warping of its crust into ocean basins and land protrusions, its wrinkling into mountains, its fissurings and faultings, its risings and fallings, its volcanoes and its earthquakes, have been usually regarded as the natural sequences of a cooling globe. So, too, the consumption of the atmosphere in the formation of the oxides, carbonates, and carbonaceous deposits, and the absorption of the ocean into the body of the earth, are current doctrines founded on the Laplacian hypothesis.

Supporting phe a.—In favor of the Laplacian hypothe stand the **unquesti** ts that the interior of the earth is hot molten rock has been extruded from it at various the known geologic ages, and that the earliest known igneous or igneous derivatives. In its favor also long list of beautiful harmonies in the solar system, symmetry have been thought to tally well with th tion of its members as successive rings.[1]

Objections to the Laplacian hypothesis.—Not very general acceptance of the Laplacian hypothesis century, certain objections have all along been urge recently certain new ones of a cogent nature have b consideration.[2]

(1) As already noted, it has been urged that de not be formed, but that the equatorial matter woul separate particle by particle.

(2) It has been questioned whether the rock subst in the attenuated condition it must have had in th moon ring would not have cooled to solid particles lo have collected into a spheroid.

(3) By mathematical investigation, Moulton ha that there are grave mechanical difficulties in the ring into a spheroid as simply and promptly as sup and this gives new point and force to the preceding o

(4) It has been urged that in so highly heated a hypothesis assumes, the molecular velocities of the the ring would be so great that they could not be the attraction of the ring, and perhaps could not b by the gravity of the supposed gaseous spheroid.

(5) It is a most singular fact that Phobos, the Mars, revolves in less than a third of the time of tion, whereas, according to the Laplacian theory, of rotation should have kept on increasing after the

---

[1] A full list of these is given in World Life by Alex. Winch

[2] A Group of Hypotheses bearing on Climatic Changes, Jour. 1897, pp. 653–83; An Attempt to Test the Nebular Hypothesis Masses and Momenta, Jour. Geol., Vol. VIII, No. 1, January 58–73; Certain Recent Attempts to Test the Nebular Hypothes August 10, 1900, T. C. Chamberlin; An Attempt to Test the Appeal to the Laws of Dynamics, Astrophys. Jour., Vo 103–130, F. R. Moulton.

Phobos was detached. To explain this difficulty, G. H. Darwin has suggested that tidal retardation may have decreased the planet's rotation much more than the contraction increased it, but this seems highly improbable. Furthermore, Moulton has shown that the particles that make up the inner edge of the inner ring of Saturn revolve in about half the planet's time of rotation, and that the tidal argument, applied to Mars, does not fit this even more singular case without making new and inconsistent assumptions.[1]

(6) But perhaps the most severe test to which the Laplacian hypothesis has recently been subjected is founded on a study of the relations of mass and momenta. It is a firmly established law of mechanics that the moment of momentum of any freely rotating or revolving system, like the nebula in question, remains constant, if not influenced from without, whatever changes the system may undergo; and this principle is peculiarly well adapted to test the evolution of the solar system. Now Moulton has shown[1] that if the solar system be converted into a gaseous spheroid, so expanded as to fill Neptune's orbit, and so distributed in density as to conform to the recognized laws of gases, and if the whole moment of momentum now possessed by the solar system be given to it, it will not have a rate of rotation sufficient to detach matter from its equator, and would not acquire such a rate until it had contracted well within the orbit of the innermost planet.

(7) If the method be reversed and the expanded spheroid be given the successive rates of rotation necessary to develop the rings at the requisite stages, the moment of momentum of the system at each ring's birth should equal the existing moment of momentum of the derived bodies. But Moulton's computations show that, at the stage that gave birth to the Neptunian ring, the moment of momentum of the restored nebula must have been more than 200 times as great as the present moment of momentum; in the Jovian stage, it must have been 140 times as great; in the earth stage, 1800 times as great, and in the Mercurial stage, 1100 times as great. Here is not only an enormous discrepancy, but one that varies greatly and irregularly from stage to stage. This seems to show that the discrepancies cannot be due to any failure of the law of density of gases to hold good, for that should give a consistent systematic error.

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[1] Loc. cit.

(8) So again, if the ratios of the masses separat
stages be compared with the momenta they carrie
able discrepancies arise. In this case the momen
the parent nebula at any stage may be computed
of momentum of its derivatives, and so all doubts t
the distribution of density in the nebula be avoi
the mass of the supposed ring that formed Jupiter
less than one-thousandth part of the solar nebula at
the ring was separated; but Jupiter and his moo
95% of the total amount of moment of momentum
at that stage. In other words, the Laplacian
the proposition that in a rotating gaseous sphe
ring equal to less than one-thousandth of the whole
by centrifugal acceleration, carried off 95% of th
momentum, which seems incredible. A similar
separation of other rings gives like extraordinary
results, as in the previous case, vary greatly and
themselves, showing a lack of system or consisten
process of ring detachment.

The inquiry along these lines, being of a somewha
cal nature, throws grave doubt on the validity of the
sis. It seems to show that the solar system mus
ized so that a very small fraction of the matter (i.
satellites, which amount to about 1/700 of the w
nearly all (97+%) of the moment of momentum
3% in the central body that carries all of the mat
fraction named. It is difficult to see how this coul
ting spheroid. Tidal reaction, by transferring m
central to the outlying bodies, may help slightly
difficulty, but computation shows that it is utt
meet the case.

(9) Under the Laplacian hypothesis the satellite
in the direction in which their planets rotate. Th
ninth satellite of Saturn revolves in a direction op
and the inner satellites.

Unfavorable testimony of existing nebulæ.—The
cian hypothesis has been still further weakened
though the knowledge of existing nebulæ has rece

very greatly by photography, nebulæ have not been found which present a series of such systematic annulations as the hypothesis postulates. On the contrary, the spiral nebula, as announced by the late Professor Keeler,[1] is found to be the dominant type.

II. THE METEORITIC HYPOTHESIS.

A simple but untenable form.—It was long ago noted that, from time to time, fragments of stony and metallic matter fell from the heavens, and that shooting stars entered the upper atmosphere nightly in great numbers; and out of this naturally grew the suggestion that the earth may have been built up in this way, save that the process was rapid in the early ages before the heavens had been so thoroughly swept of meteoritic material. This form of the hypothesis, however simple and natural, may be dismissed without serious consideration, for the distribution of meteorites, their directions of motion, and their velocities are such as to forbid the belief that the solar system, with its symmetrical discoid form and its many peculiar and significant features, could have been formed from them *directly* in the manner supposed.

The hypothesis of Lockyer and Darwin.—In a work entitled "The Meteoritic Hypothesis" Lockyer has endeavored to show that nebulæ are composed of meteorites sparsely aggregated into swarms, and that stellar systems are evolved from them. His hypothesis is, therefore, nebulo-meteoritic, and relates to a stage antecedent to the formation of the planets. He assigns the light of the nebulæ to the collision of the meteorites with one another. To meet the fact that the spectra of some nebulæ are of the gaseous type, he assumes that the impact vaporizes a part of the meteorites, and these vaporized portions give forth the gaseous spectra. It remains to be explained, however, why the spectra of these nebulæ rarely show anything but hydrogen, helium, and an unknown substance, or substances, provisionally called nebulium, and are never known to show metals. The continuous spectra which other nebulæ present he refers to the solid or liquid portions set aglow by collision. The luminosity of any given meteorite arising from impact must be very transient, but the hypothesis assumes that the aggregate result of many such collisions is a nearly constant emanation

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[1] Astr [illegible] Journal, June, 1900, pp. 347, 348.

**of light. Lockyer's treatise does not enter into ɪ
of the mechanics involved in the original gather
nebular swarm, nor does it attempt to trace the
down to the origin of the planets and the specific g**

In a very notable paper,[1] George H. Darwin, ɪ
swarm *already aggregated* and already possessed o
tribution suited to the formation of the solar sys
discussed its mechanical characters. The essential
ous inquiry is the conclusion that such a swarm is
gous to a gas, and that the laws governing gases m
discussion of its mechanical properties. He does r
the history forward into the development of the pla
believes that they arose from equatorial detachme
cian hypothesis. In its immediate application t
earth, this special form of the meteoritic hypoth
to become practically identical with the gaseous h
to be subject to the criticisms urged against that
those arising from the relations of mass and momen
the most grave.

There arises also the question whether such a
would not *actually pass into the gaseous condition*,
heat developed by the frequent and violent collisio
To the swarm under investigation, Darwin assigne
the radius of the earth's orbit, which involves a c
persion. At even this dispersed stage, he comput
the region of the present earth's orbit, would oc
or more per day, and at an average velocity of thr
second. With this frequency and velocity, it w
meteorites could not long escape comminution an
the comminution and vaporization progressed, an
densed, the frequency of the collisions must hav
escape of the augmented heat, so caused, must b
more obstructed. The logical conclusion seems t
passage into the gaseous condition would ensue.

As this form of the meteoritic hypothesis th
into the gaseous one, dynamically, if not literall

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[1] On the Mechanical Conditions of Swarms of Meteorites
, Phil. Trans. Roy. Soc., 1888.

stage of the earth is reached, it is not needful to follow it further here, where the origin of the earth is the subject of quest.

Is some other form of the meteoritic hypothesis tenable?—Is it possible to postulate, on probable grounds, some other phase of meteoritic assemblage that will continue to be meteoritic throughout its evolution down to the formation of the earth, and give distinctive geologic results? Prolonged efforts on the part of one of the authors to frame such a hypothesis, in definite terms and in a workable form, have been attended by unsatisfactory results only. The difficulties are very grave. On the one hand are dispersive agencies that tend to keep up the scattered condition of the meteorites and to prevent assemblage; on the other hand, if a tendency to assemblage be established, the growing swarm seems sure to merge either into the gaseous or quasi-gaseous condition, as above outlined, or else into the planetesimal system presently to be considered. The true meteoritic condition appears to be an expression of a dispersive function which tends to produce and to perpetuate a scattered state. An adequate discussion of the possibilities and limitations of meteoritic assemblage is beyond our limits, but there are involved certain fundamental facts and principles of no little importance to the philosophic student of geology who wishes to probe, as well as he may, the basal postulates of the earth's genesis, and these merit attention. The subject, to be sure, is essentially astronomical, but as geology is the domestic chapter of astronomy, the geological student is entitled to go as far afield as his problem requires.

The two general conceptions of the origin of the meteoritic state.—Conceptions of the ulterior origin of the dispersed condition from which evolution may be supposed to start, fall into two general classes: (1) a primitive diffuse condition, without previous assemblage, a kind of original chaos; or (2) a derived condition of dispersion arising from the scattering of previous assemblages or the disruption of previous bodies. If in the second case the dispersion be so great as to project the disrupted material beyond the sphere of its own gravitative control, its condition becomes dynamically the same as if it originated in such a dispersed condition. It is therefore only necessary to consider those cases of this class in which the scattered matter remains under its own gravitative control and constitutes a diffuse flock or swarm of small bodies.

1. *Assemblage from a Primitive State of Di*

Conditions affecting the initiation of a meteoritic s ing of a meteoritic swarm, theoretically, from di moving in diverse directions, as typical meteorites grave obstacle in *the high ratio of the kinetic energy* *their mutual gravitation.* Since gravitation is the ag and the kinetic energy of their motion is the disp obvious that if the potency of the latter is superior to the conditions for gathering meteorites into a swa least in general. The relations between the kinetic e and their mutual gravitation therefore require consi feature.

The velocities of meteorites.—While the velo have been only approximately ascertained, betwe been directly measured and those that have been e dental facts, they are sufficiently well known for the discussion. The meteorites which are seen in the earth from behind, and since the earth is moving average rate of 18.5 miles per second, these meteo it with a velocity sufficiently in excess of this to b in passing into the atmosphere. From present velocity of meteorites, when they encounter the ea estimated to be between 20 and 30 miles per se the velocity appears to reach 40 or 50 miles per sec The velocities of meteorites seem to be of the same ties of the stars, whose average has recently been at 23 miles per second. This of course is merely t that have been thus far measured, and will doubt additional measurements; but this velocity may representative of the velocities of stars and of me of the sidereal system.

Now to give to the meteoritic hypothesis the tions, let all the matter of the sidereal system be verted into meteorites, and let these meteorites have and velocities identical with the parent bodies. to assign them these motions to preserve the mo e system as the laws of mechanics require. V of primitive chaos in which movements in all directions, with velocities varying greatly, but averaging twenty odd miles per second, prevail. The critical feature is the prodigious kinetic energy which so high an average velocity involves.

Now the only effective known force which might draw these flying meteorites together into swarms and keep them together is their mutual gravitation. Electric and magnetic attractions might do a certain auxiliary work under special conditions; but as these attractions are accompanied by neutralizing electric and magnetic repulsions, the differences between them may probably be neglected.[1] We must, therefore, inquire how the controlling power of gravity compares with the amount of kinetic energy that must be overcome.

The mutual gravitation of small bodies is extremely feeble. For example, Moulton has computed that if two spheres having specific gravities of 10 and diameters of 10 feet, and hence each weighing 164 tons, be placed 100 feet apart and be wholly unaffected by any other force than their mutual attractions, practically half a day (11.66 hours) will be required for them to draw themselves together, when each has to go only 45 feet. Their mean velocity is therefore less than four feet per hour, a scarcely perceptible motion. If they were separated to an infinite distance and allowed to fall together, and thus to develop the highest possible velocity which their mutual attraction could produce, it would not exceed .012 feet per second (Moulton). It is obvious, therefore, that if the supposed primitive meteorites moved at the assigned velocities, or at velocities even remotely approaching them, they would be quite beyond the gravitative control of one another individually. Such meteorites, moving in opposite or transverse directions, would pass by one another without appreciably deviating from their courses, unless they chanced to collide. In that case they would probably be shattered and dispersed, because on the average they would strike at velocities many times as great as the projectiles from the best modern guns. If they remained unbroken, they would, if perfectly elastic bodies, exchange velocities and directions, or, if perfectly inelastic bodies, would combine their momenta, unless they

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[1] We are here speaking of the ordinary phenomena of electrical and magnetic attraction and repulsion, as commonly understood; not of those newer and profounder interpretations which assign inertia and other phenomena, including even gravitation itself, to [illegible] agnetic agency; much less the radical views involved in the electromagneti [illegible] of matter.

were driven apart by the explosive force of vapors f
points of impact, as suggested by Darwin. As most bo
perfectly elastic nor perfectly inelastic, an intermediat
usually follow. In exceptional cases, the velocities
enough to permit inelastic bodies to weld together, but
chances of disruption, or of elastic rebound, would b
greater than those of welding. Even in the case of wel
is merely a larger meteorite in lieu of two smaller ones, a
is made in the starting of a meteoritic *swarm.* Beside
meteorite is subject to disruption by succeeding violent

The possibilities of parallel movement. — Appare
working chance of starting a swarm of meteorites by at
these adverse conditions, lies in the exceptional case
moving in nearly parallel directions, at nearly the sa
in courses near one another. In this case the motions of
only antagonize their mutual attractions to the extent
differences of kinetic energy as may arise from their sli
of velocity and directions of motion. Under extremely
ditions of this kind, two meteorites might come into n
tive control and revolve about their common center of
a third one might join them under like conditions, and s
plane of revolution of the third meteorite might chance
with that established by the pair it joined, or it migh
its direction of revolution might or might not be the sam
fore extremely unlikely that the planes of revolution of a
number of meteorites, coming thus together, would be
mately identical, or that the directions of their revolu
coincident, and hence opposite and cross revolutions
with obvious liability to collisions, so that, in the end, th
perhaps develop into a quasi-gaseous condition.

A possible alternative, if the material were suffic
might be the mastering and killing out of the movements
of the group by the majority through a long series of
the development thereby of a common direction of revol
case the system would take on the orbital, rather than th
and fall under the planetesimal class.

The danger of dispersion.—It must be noted, how
conditions for starting the growth of such a swarm—

adjacent movements at nearly equal speeds—are very exceptional, and hence the accessions in any given period must be presumed to be few compared to the whole number of meteorites that pass the place of the initiating swarm; for all those that have opposite and transverse courses of any appreciable angle, and all those that, though moving in parallel directions, have appreciably different velocities, will pass through the point of assemblage with dangerous differential velocities. They are therefore liable to break up the initiating swarm by colliding with its members and driving them beyond its gravitative control. This contingency is especially great while the swarm is small, and its gravitative command of its members feeble. Hence arises the question whether the swarm's peril of destruction is not greater than its chance of growing to a self-protecting size, so incomparably greater, indeed, as to render the method an extremely improbable one.

If such a swarm succeeds in reaching a large mass, the probabilities of its holding its own members and of capturing the colliding meteorites, become very favorable. The growth of a meteoritic swarm or of a nebula *after it has once gained a sufficient massiveness,* is therefore simple enough and probable enough; but the starting of a swarm, and the early stages of its growth, are attended by extremely unfavorable contingencies.

The sparseness of distribution and its bearing.—The extreme tenuity of the celestial matter hypothetically thus dispersed is another vital consideration. The light of a star in a flight of 50 years, at the speed of 186.000 miles per second, does not seem, on the average, to encounter enough dark matter to seriously dim its brightness. All the matter that lies between us and the outermost visible stars does not cut off as much light as the thinnest cloud. On a most liberal estimate of the amount of meteoritic matter encountered by the earth at present, it is computed that it would take a billion years to add an inch to its surface.[1]

If all the matter now aggregated in the stellar system, on any reasonable estimate of its mass (and the known distribution and movements of the celestial bodies limit such an estimate), were distributed through the space now occupied by the stars, it would not help the case much, so far as meteoritic assemblage is concerned. To illustrate, if the matter of the solar system were scattered through the space about

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[1] Young's Astronomy, p. 475; Woodward, Astr. Jour. 1902.

it, stretching out half-way to the nearest stars, its
such that, if the orbit of Neptune were the hoop of a
000,000 miles in diameter, and were sweeping thro
the rate of 12 miles per second—the approximate v
with respect to the stars—it would take some 900,
for it to sweep up the scattered matter. This is prob
illustration of the average tenuity of the supposed di
star-grouping about the sun is probably as dense as t
whole. This tenuity immeasurably transcends the
the most effective air-pump. It would be an extrava
use of terms to call this a "meteoritic plenum." M
is fundamentally dangerous. The matter in the hea
small in proportion to the space—almost inconceiv
extreme sparseness of distribution means that the p
the stellar system is enormously great in proportion
matter. The factors then that weigh in the study of
blage are not simply, or even predominantly, matte
but also, and particularly, space and motion.

The time factor.—With such excessive tenuity of
when all known matter is converted into meteorite
potent obstacles to assemblage as are imposed by
energy of the meteorites, it seems an imperative co
growth of a meteoritic assemblage having the mass o
must require a period quite beyond comprehensio
to the question whether a swarm of meteorites could
as a swarm, through such a prodigious period. M
first assembled pass on through its own evolution, w
be, without awaiting the excessively delayed assem
portions? If the members of the swarm were in colli
postulated by Lockyer and Darwin, must not the kin
earlier assemblage have been exhausted long before t
later part? In other words, must not the first a
solid at a relatively early stage in the process, and th
accessions be added individually, as meteorites are
sun and planets? Is it a tenable view that the me
swarm should go on, without attendant evolution
necessary for a solar system is attained, and then,
enter upon an evolution into a sun-and-planet syste

was organized on the collisional basis, nothing but a negative answer seems possible. If the meteorites could be supposed to come together so as to revolve in harmonious orbits about a common center, on the planetary basis, the assemblage might be perpetuated, but this takes the case out of the typical meteoritic class, and carries it over to the planetesimal.

Under the conditions of the case, it is not apparent how a meteoritic nebula of the quasi-gaseous or collisional type can grow up *de novo* by the assemblage of dispersed meteorites, or by the aggregation of chaotic matter, if the material were endowed with the present momentum of the system.

2. *Derivation from Previous Aggregates.*

If the origin of the nebula be assigned to the dispersion of some previous large body, three phases are conceivable: (*a*) dispersion by explosion, (*b*) dispersion by collision, and (*c*) dispersion by tidal disruption.

(*a*) **Dispersion by explosion.**—The diffuse state of the parent nebula may perhaps be assigned to explosion, following the analogy of one of the hypotheses of the origin of new stars, though it is difficult to assign any probable and adequate cause for such explosion. But if it takes place, the dispersing force must obviously be radial, in the main. and after the matter has made its outward excursion and is arrested by gravitation, it must return on nearly direct lines and collide at the virtual point of departure. The result of this collision, if the dispersion have nebular dimensions, must be the development of enormous heat and the probable conversion of the whole into a gaseous body. If so, the evolution must thence proceed along gaseous lines. In this case. nothing properly analogous to a meteoritic condition is likely to be developed in the system, except as a mere incident, and the case does not really belong under the meteoritic hypothesis. Such an explosion may indeed give rise to material shot away beyond the control of the system, and this part might be truly meteoritic, but it would be lost to the system, and fall under the case already discussed.

(*b*) **Dispersion by collision.**—If the dispersion be assigned to the collision of two large bodies, as postulated by Croll[1] and others, the heat developed must be presumed to be great enough to convert the

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[1] Croll, Climate and Cosmology, 1889, pp. 297–315.

main mass into a gaseous state. If the collision \
center encounter, a radial dispersal of matter trans
of collision would follow; returning from which, th
again collide, and after a series of oscillations would
down into a pulsating gaseous mass.[1] Here again t
become gaseous at the outset, and probably develo
typical meteoritic kind except possibly such spor
might be projected beyond the control of the system.
were excentric, a rotatory motion would doubtles
upon the radial motion, and the case would either fal
ous or the orbital system, or under a combination o

(*c*) **Dispersion by tidal disruption.** — It has rec
gested that bodies passing close by one another, b
may suffer disruption through their differential attr
internal elasticity,[2] on the principles developed by
and others. In this case the disrupted elements are
movement in a common direction and in the plane o
initiating it. The dynamics of the system are therefo
set definitely of a rotatory or revolutionary kind, a
under the orbital or planetesimal system rather tha
system.

It appears, therefore, that neither explosion nor c
disruption is likely to give rise to a distinctively m
and no other definite source is known to us. *Indi*
and rotatory or revolutionary assemblages of dis
as well as true gaseous nebulæ, may be supposed t
catastrophes named, but apparently these catastrophe
priate agencies for producing fragmental *swarms* of
meteoritic type.

The Evidence of the Meteorites Themsel

The origin of meteorites bears on the question w
the essential material from which stellar systems are

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[1] A case of this kind is described by Kelvin, Popular Lectur
1891, p. 413.

[2] On the Possible Function of Disruptive Approach in the Fo
ites, Comets, and Nebulæ, T. C. Chamberlin, Astrophys. Jour., V
17–40, and Jour. Geol., Vol. IX, 1901, p. 369.

merely the incidental products of such systems, and dependent on the pre-existence of the systems.

Theories of the origin of meteorites.—Meteorites have been regarded (1) as matter projected from the earth by volcanoes and brought back to it, (2) as matter discharged from the moon, (3) as matter ejected from the sun or from stars, (4) as dispersed matter from exploded stars, (5) or from exploded planets or satellites, (6) as the residue of scattered comets, (7) as fragments of tidally disrupted atmosphereless bodies, such as asteroids and satellites, and (8) as accretions of gas or fine particles of matter in open space.[1] All but the last presuppose the existence of the present solar system. Some of them further assume, by implication, that the meteorites constitute merely minute detachments from the present system. A volcano cannot shoot away any great part of the body of which it is itself, at best, but a small dependency. Only those dispersive hypotheses of this group that postulate the disruption of suns or stars carry any presumption that suns or stars would again be formed from them, for lack of mass. The last hypothesis alone assumes a *primary* organization. If meteorites are collected in space, as rain-drops are gathered in the atmosphere, and if they then unite to form solar systems, either through nebulæ or more directly, they are the source of such systems in as true and radical a sense as rains are the sources of lakes. The characters of meteorites should decide between these alternative views.

The characters of meteorites.—Among the distinctive and significant characters of meteorites are: their fragmentary forms, their brecciated structures in part, their occasional slickensided surfaces, their veins, the glassy nature of a part of their material, the amorphous nature of another part, and the crystalline nature of still a third and larger part, the variations in the coarseness of the crystallization, the extraordinarily large crystals of the nickel-iron, the inclusion of non-metallic crystals and nodules in the nickel-iron crystals, the scattered condition of iron crystals or lumps among silicate crystals in many cases (sporadosiderites), the large proportions of the nickel-iron and the magnesia, the presence of peculiar spheroidal aggregations (*chondri*), the fragmental nature of the chondri in many instances, the absence of water and hydrates, the absence of free oxygen, the absence of a group of minerals common in terrestrial igneous rock orthoclase, the acid plagioclases, the micas, the amphib(nephelite, the presence of certain unstable chlorides, phosphides unknown in the earth, and the presence combustible hydrocarbons.

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[1] For an excellent summary of the structure, constituents, and theories of meteorites see Farrington, Jour. Geol., Vol. IX, 1901, pp. 51, 174, 393, 522, and 623.

The bearing of these characters.—These make up group of characters, whose origin can only spring fr peculiar combination of conditions.

While the fragmental condition of many meteorit(

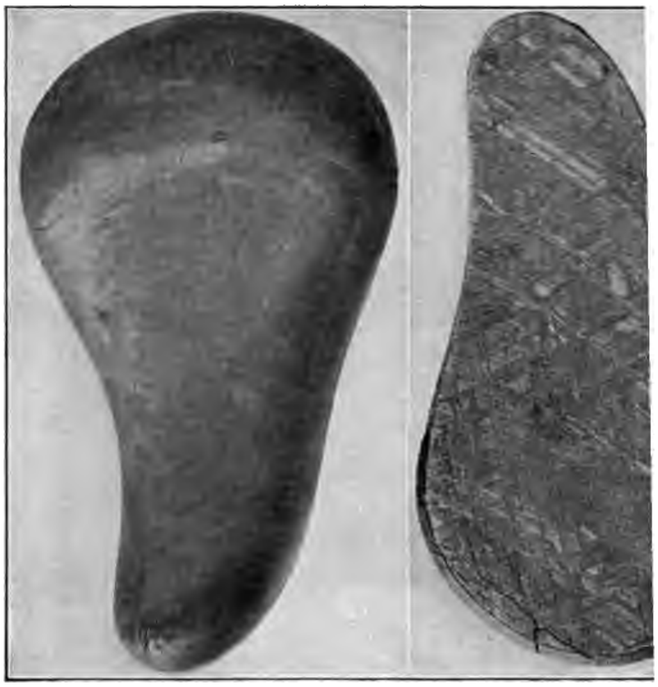

Fig. 1. Fig. 2.

Figs. 1 and 2.—A meteorite of exceptionally symmetrical form anc one of the very few whose external form suggests a possible accre and here introduced on that account. The truncated crystals of Fig. 2, however, show that it is reduced from a larger mass of unk coarseness of the nickel-iron crystals and their arrangement gi that the mass grew by accretion from a central nucleus. The iron) meteorite, 3×5 inches. New South Wales. (After A. Liv(

the earth, is due to fracturing in their passage through are indications that they already had a fragmental fo entered the atmosphere in many, if not most, cases. This implies that they are portions of larger bodies, and that they were not aggregated, as such, in free space (Figs. 1, 2, 3, and 4). At least this appears true in the case of most of the more massive meteorites that reach the surface of the earth. This of itself does not exclude the view that meteoroidal aggregation may take place in free space, and that the aggregates may have entered into the make-up of the larger body from which the meteorites were derived. It, however, bears on the question whether meteorites, as a rule, were organized, as such, by the

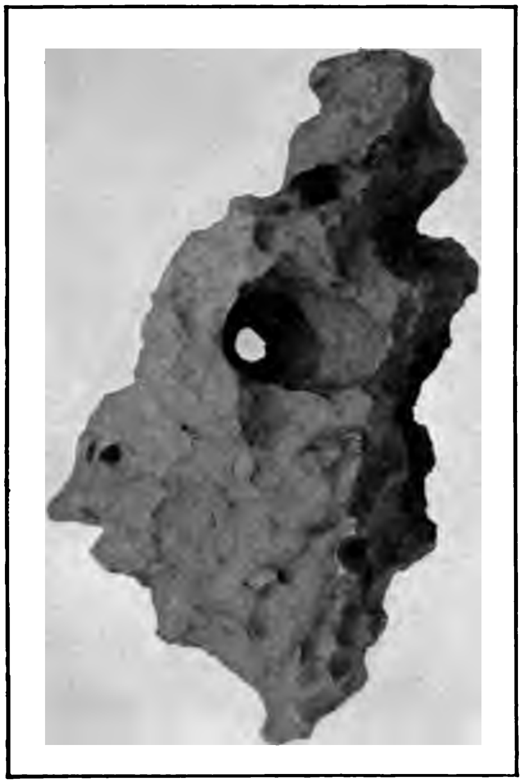

Fig. 3.—A nickel-iron meteorite of irregular form, showing obviously that it is but a fragment or remnant. The pits of the surface are due to the removal of the less stable material, probably silicates or metallic compounds, by which the nickel-iron was surrounded. Canyon Diablo meteorite, 265 lbs. Field Columbian Museum. (Photo. by O. C. Farrington.)

gathering together of gaseous matter or scattered space.

More direct evidence is found in the fragmental of the stony meteorites. Among the broken elem

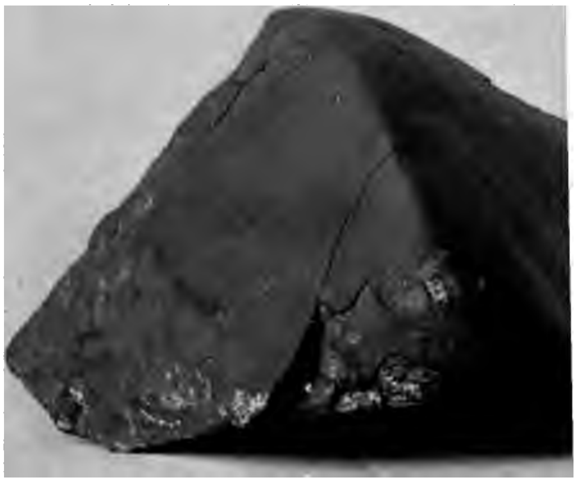

FIG. 4.—A stony meteorite showing fragmental outline smoothe through the air, with smaller fracture surfaces due to ex course. The Saline, Kans., meteorite. Field Columbian Farrington.)

of chondri (Fig. 5). As the chondri are aggregations ites, their fragmentation implies disruption and re- parent body, or at least disruption in an earlier stag Point is added to this by the occurrence of larger fragments of smaller ones (Fig. 6). A very singula is presented by the Mount Joy meteorite, which is iron fragments (Fig. 7). These various evidences imply a previous history affected by successive co tion and fracturing.

The presence of slickensided surfaces (Fig. 8) body subjected to varying stresses, resulting first afterwards in the rubbing of the fissure walls upon existence of veins also implies fracture attended by s

The general prevalence, but partial absence, of crystallization, and the kinds of crystallization imply varied thermal conditions in the parent body. The amorphous condition implies the absence of fusion and of the conditions of crystallization. The glassy structure equally implies a molten state followed by quick cooling, while the various grades of crystallization imply high temperatures variously sustained.

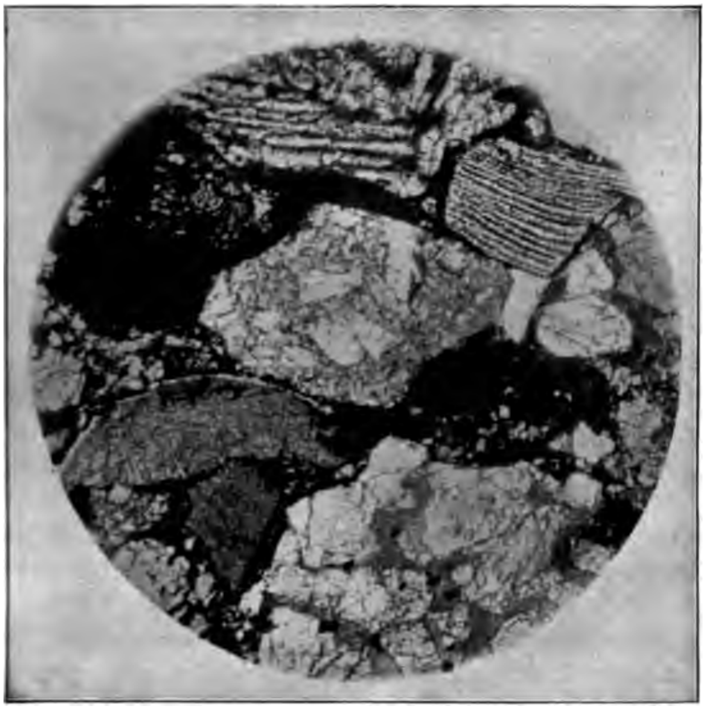

FIG. 5.—Section of the Mezo-Madaras meteorite, showing a meteoritic tuff made up of fragments of chondri. Portions of bronzite, chrysolite, and nickel-iron chondri can be recognized. (After Tschermak.)

The extremely large crystals (Figs. 9 and 11) suggest protracted high temperature with conditions favorable for a systematic rearrangement of the material. At the same time the cases in which the metallic iron is scattered through the silicate material (Fig. 10) seem, at first thought, to imply the absence of a thoroughly fluid state at the time the segregation of the iron began, since a massing of the heavier metallic material toward the center of gravity would naturally be expected, just as in a blast-furnace metallic iron promptly separates from slag·

but the presence of such scattered lumps of iron
land[1] at least limits the force of the inference.
the mass was very viscous, or that the metallic
mately diffused through the rock-substance pr

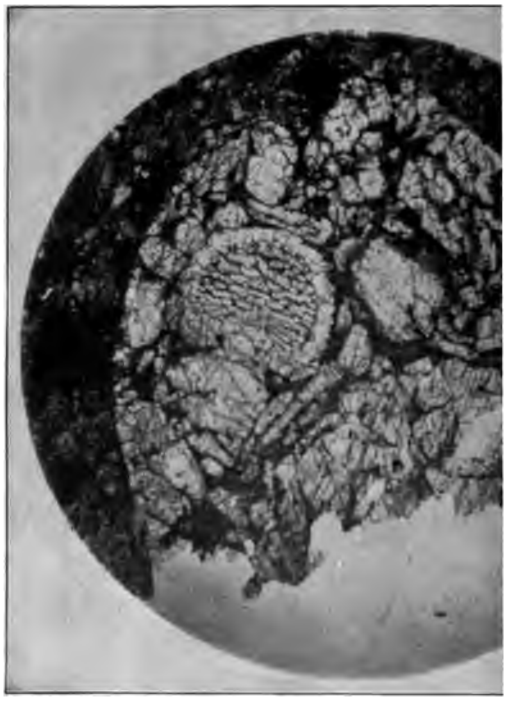

FIG. 6.—Section of the Dhurmsala meteorite, showing a chondrus inclosing a smaller monosomatic one. Bot
lite. ×8. (After Tschermak.)

of crystallization, or that the motion of the mol
to permit gravitative segregation, or that the
their effects. In addition, it is to be noted
temperature, acting on a mixed mass of mate
tions suitable for slow aggregation and cry
without the melting-point being reached, and
one of the agencies by which these singular com

It is hard to believe that these coarse cry taken place in small masses of matter projected into space in the molten condition, and the view that meteorites are formed directly from lavas shot into space by volcanic or other explosive action, as from a sun, a planet, or the moon, is, therefore, unsatisfactory. Equally adverse to this view is the extraordinary fact that certain classes of meteorites are formed chiefly of *hydrocarbons* which are volatile at moderately high temperatures, and are readily combustible. These hydrocarbons seem prohibitive of high temperatures at all stages of their history, and it is a marvel that they should survive the transit through the atmosphere; but this is probably due to the fact that the meteorites were excessively cold when they entered the atmosphere and, during the brief time of transit, were only superficially consumed, while their interiors remained cold, as the interiors of meteorites are not infrequently found to be, immediately after their fall.

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[1] For a careful description and figures, see The Rocks of
W. C. Phalen, Smithsonian Misc. Coll., Vol. I. Pts. 1 an

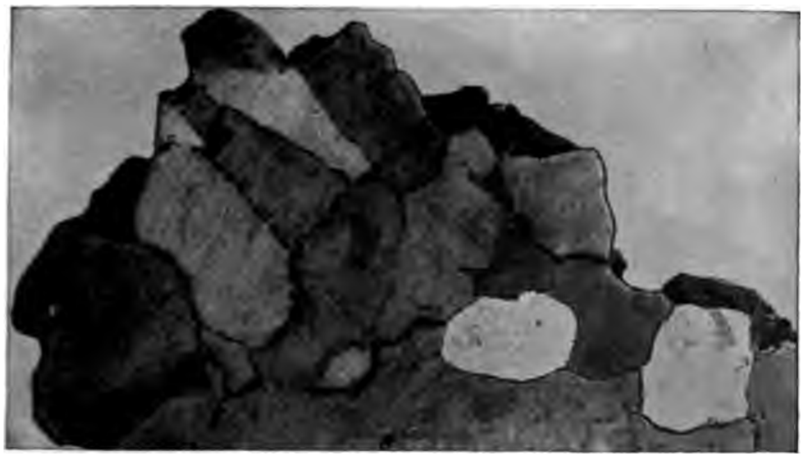


Fig. 7.—Section of the Mount Joy meteorite, nickel-iron, showing brecciated structure. Field Columbian Museum. (After Farrington.)

Igneous processes on the earth give rise to magmatic differentiation resulting in a familiar series of minerals which make up large portions of the crystalline rocks of the earth's surface. So also, weathering and solution remove more of the basic than of the acidic constituents of crystalline rock, and when the residue is metamorphosed, a similar series of minerals arises. Among these are quartz, orthoclase, the acid plagioclases, the micas and the amphiboles, a group absent fro the meteorites. Their absence suggests that, in the parent body, n matic differentiation of this kind, as well as selectiv not take place. This, however, does not necessarily action, nor nonhydrous weathering, but merely the of weathering and magmatic differentiation that pre and probably in similar bodies having atmospheres a

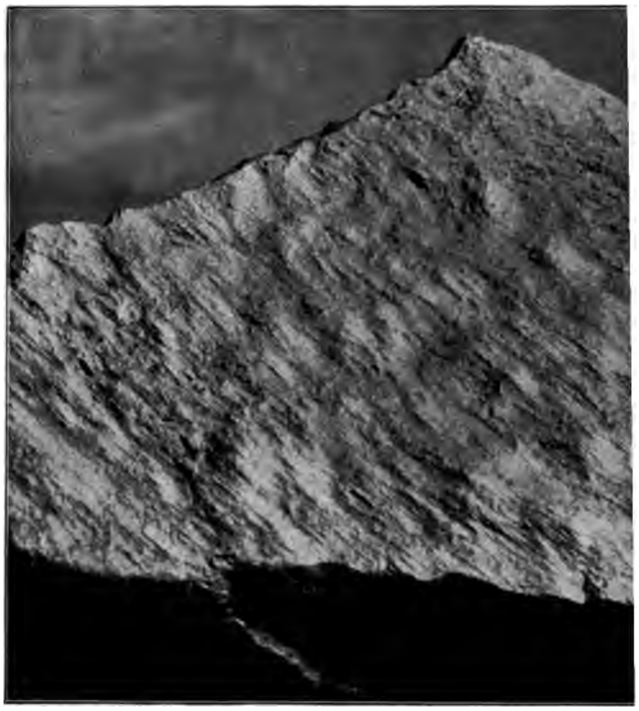


FIG. 8.—A slickensided surface of the Long Island meteorite, Columbian Museum. (After Farrington.)

The absence of water, of hydrates, and of free testimony against the derivation of the meteorites fr bodies like the earth.

The high velocities and the diverse directions of flights relative to the earth forbid assigning their or to volcanic action in the moon or any of the planets. S might be given by a solar explosion, but the directions and not promiscuous. Explosive action within the so have made an occasional meteoroidal contribution, but scarcely more than that.

Taken altogether, the combination of characteristics presented by meteorites seems to fail of satisfactory explanation on any hypothesis of their direct derivation from a sun or star, or from a planet surrounded by a hydrosphere or an oxygen-bearing atmosphere, or from any planetary body affected by mineralogic differentiations of the terrestrial type. No more do they seem to find satisfactory explanation in simple accretion in free space.

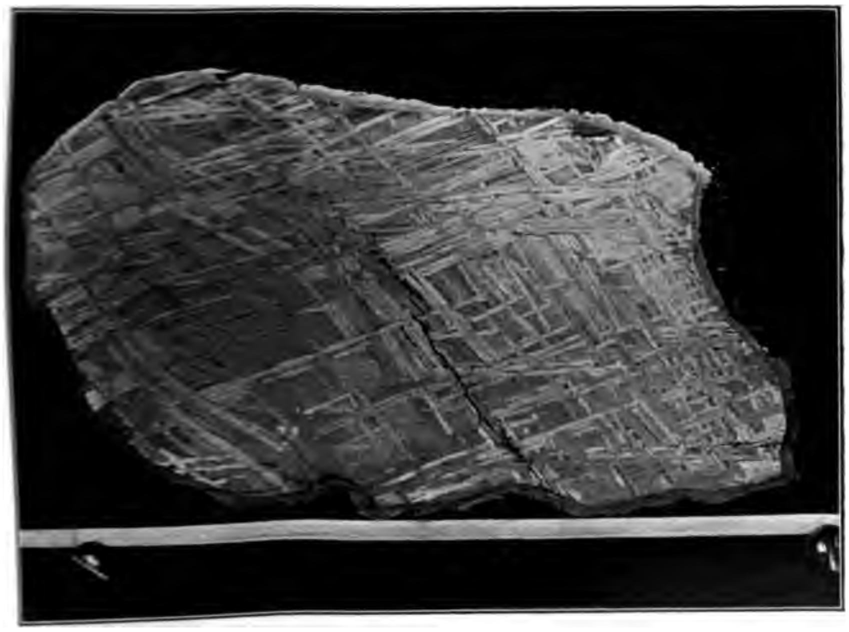


Fig. 9.—Section of the Franceville meteorite, showing the coarse crystallization of the nickel-iron (Widmanstätten figures). Ward-Coonley Collection. (From H. A. Ward.)

Possible derivation from atmosphereless bodies. — It remains to inquire whether small, atmosphereless bodies, like the asteroids and the satellites, afford a more probable source, or whether new hypotheses must be sought. Small celestial bodies are believed to be devoid of atmospheres and hydrospheres because their gravity is too low to overmatch the molecular velocities of the atmospheric gases and the vapor of water. This interpretation carries the corollary that they never have had permanent atmospheres and h thus meet the requisite explanation of the absence of If built up by accretion, they should contain the material, and, if formed in some other way, they variety. In their different parts, they may present tural characteristics. The asteroids and satellites subject to deformations, attended by fractures, slickensides and similar dynamic phenomena. Eru

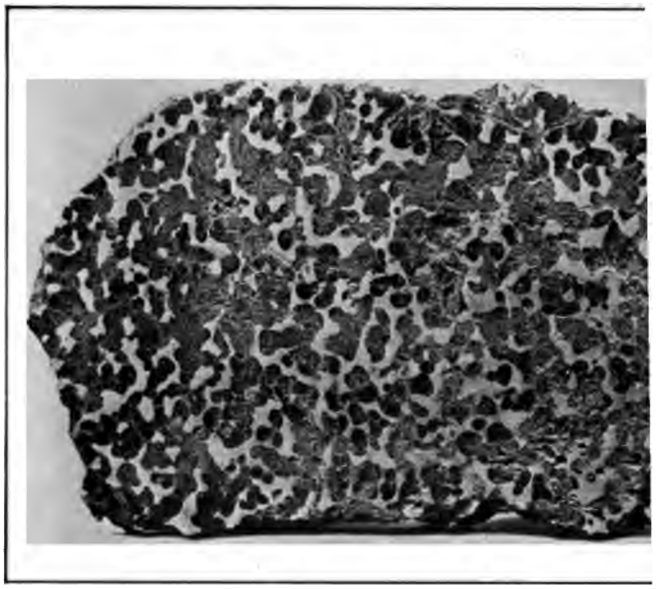
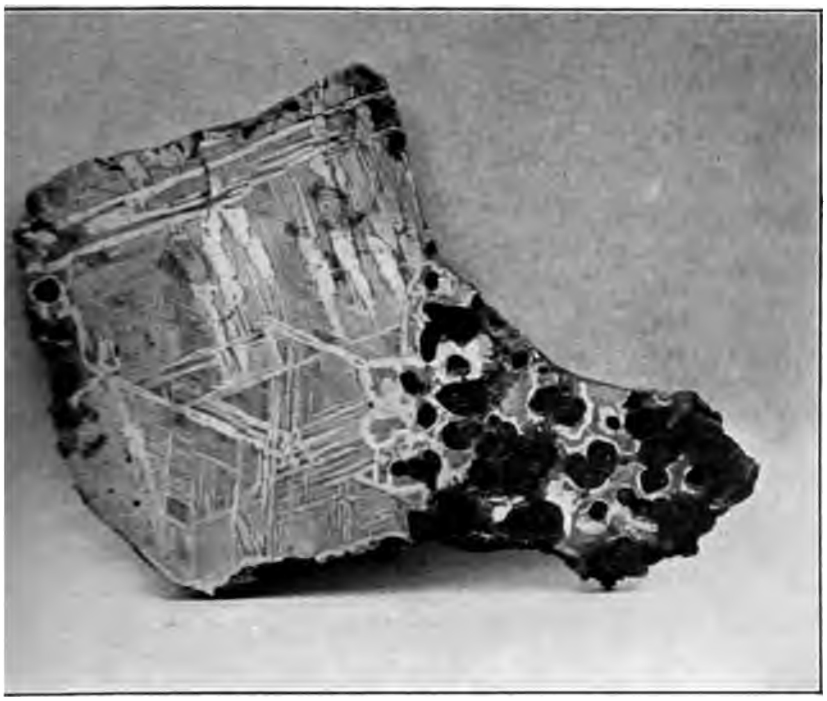


FIG. 10.—Section of the Brenham, Kans., meteorite, showing ture of nickel-iron, the light-colored portion, and silicat pounds, the dark portion. Ward-Coonley Collection. (Fro

action, as well as the impact of bodies falling from have contributed the various forms of fragmental glassy material. The absence of a protecting at their surfaces to the full striking force of falling bo disrupting effects of extreme changes of temperature. and at slight depths, amorphous material, as well as crystalline rock, may have been formed. At greater ing conditions of pressure and temperature requisite and coarser crystallization may have been posses ons may be assigned to inorganic action within the asteroidal , the material being derived from the hydrogen and carbon gases undantly occluded in meteorites and crystalline rocks, the requi- emperatures and pressures being supplied by the internal compres- of the body.

n these small bodies, then, it is perhaps possible to find that



1.—A partial section and a portion of the exterior of the Brenham (Haviland), ns., meteorite, showing, in close relations, a coarse crystallization of nickel- n and an intersegregation of metallic and non-metallic material, implying at the same general conditions affected both forms of aggregation. Ward- nley Collection. (From Ward.)

ordinary combination of conditions which the nature of the orites implies.

t remains to postulate a means of disruption and an agency of rsion competent to give the disrupted fragments the erratic es and the high velocities which meteorites possess, while at the time the structural features, sometimes rather perishable, escape uction by liquefaction or extreme pulverization.

Hypotheses of disruption and dispersion.—Any su
from an internal source is unsatisfactory because it is
a sufficient and probable cause for an explosion cap
a velocity of several miles per second, which wo
required to disperse the fragments beyond the contr
to which the body belonged, and because, if such s
were realized, it must apparently wreck many of the p
structures.

Collision with some other mass at a high velocit
cient to disrupt the body and to drive its fragment
requisite velocity; but the imminent danger of liq
inevitable heat of the impact, or of extreme pulveriza
material, raises doubt as to the adaptability of collis
some of the stony meteorites of large size, and of
meteorites, while it might answer well enough for m
The relative rarity of collision also suggests a second
an agency.

It has recently been suggested[1] that disruption
traction might satisfy the requirements of the case,
doubt as to adequate frequency. According to prin
by Roche, Maxwell and others, a small body passing
distance (the Roche limit) of a larger dense body
fragments by differential attraction. The size of t
ruption depends on the densities, cohesion, intern
other factors of the two bodies. For incompressible
density, Roche gives the limit of disruption as 2.44
of the large body. In most such bodies, internal
exceeds cohesion and the sphere of disruption would
The moon would probably expand with some viole
were suddenly removed by differential attraction.
this way would therefore be several times more
actual collision. The fragmentation in this case i
violent.

A small body passing near a much larger body is
from its previous orbit into quite a new one. Th
happened to several comets through the influence of

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[1] Chamberlin, On the Possible Function of Disruptive Ap
tion of Meteorites, Comets, and Nebulæ. Loc. cit.

If the orbit of the small body is such that it is caused to pass in front of the large body, say the planet Jupiter, its course will be diverted toward the sun, and its orbit shortened. If its course causes it to pass close behind the large body, its path will be diverted into a larger orbit. If a small body were to pass in this way sufficiently near to Jupiter, it might be thrown entirely out of the solar system.[1]

In these two sets of principles, there is a combination peculiarly fitted for the results required, for, by their joint action, a small body passing near a large body is liable to be disrupted into fragments, and, at the same time, to be thrown into an erratic course which may carry it entirely outside the system to which it belonged, and may give it a parabolic or hyperbolic course in stellar space. Fragmentation and dispersal by the differential attraction of very close approach escapes all of the adverse contingencies of liquefaction and pulverization incident to explosion or collision.

If the question be pushed a step farther to inquire how small bodies like the asteroids may be rendered specially subject to the requisite close approach, the answer may be found in the approach of suns, attended by such secondaries, to one another. For example, if the solar system were to pass even within five or six billion miles of a similar system, the orbits of the secondaries would be very greatly perturbed, and the balance between the centripetal and centrifugal accelerations, which now preserves the harmony of the system, would be so seriously disturbed that an intricate and prolonged series of changes would ensue. These are too complicated to be followed completely, but it is reasonable to believe that they might involve, sooner or later, the close approach of some of the smaller bodies to some of the larger. These smaller bodies in the solar system are numbered by hundreds, and the same may be suspected of other systems, and this largeness of number adds to the probabilities of some close approaches during a condition of general disturbance.

The solar system is probably not the most favorable selection for illustrating the contingencies of such disturbance, for it is a simple isolated system, with a single overpowering center that sways its attendants by a scarcely disputed control. It has swept through space undisturbed throughout the period of its present organization.

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[1] These principles have been worked out elaborately by H. A. Newton, Am. Jou Sci. 16, 1878, pp. 165-179.

But there are many binary, triple, multiple, and clus
suns which apparently divide the control of a commc
control may reasonably be supposed to involve approa
nearness to one another to seriously perturb their outl
and introduce disturbances ultimately involving disruj
The nebulous matter associated with some of these
perhaps implies something of this kind.

Relations of meteorites to comets.—The hypothe
by differential attraction goes one step farther in pos
disrupted group of fragments may, in its earlier hist
comet, since it is the general belief of astronomers t
head is composed of a cluster of small bodies. The pe
which arise from a comet may perhaps be referred
the occluded vapors and the radio-active substances
asteroid, as to any other recognizable source. The r
of the prevalence of radio-activity and allied pheno
cometic emanations less strange and exceptional than t

The fragments of an asteroid, or other small body,
manner would be given a rotatory movement by the di
tion that produced them, and hence the resulting clus
should revolve about its center of gravity in a somewh
but at the same time in more or less irregular and inh
as the result of the incidents of disruption, and this m
subject to mutual disturbance, and to frictional and g
If later conditions permitted a re-aggregation, a highly
would result.

It is now accepted as highly probable that comets, p
that have short orbits and frequently return to the vic
are gradually dispersed by the latter's differential
mutual gravity of the cometic fragments being very
ential gravity of the sun, in its own neighborhood,
to it, and the members of the cometary cluster are d
thenceforth revolve about the sun in their own indivi
spective of the other members. In other words, the
oritic fragments that constitutes the comet's head
planetesimal state by dispersion. In this we have an
tendency of a swarm to pass into a planetesimal con
allusion has heretofore been made.

These planetesimals constitute one variety of meteoroidal bodies, and it is to these that the brilliant August and September meteoritic showers are assigned. It has not been quite demonstrated that they are identical with the iron and stone meteorites above described, for they do not generally reach the earth, and it is not positively known that they have done so in any case, though one case of high probability is known; but their essential identity is extremely probable. In the fact that they have come to have individual orbits about the sun, and that these orbits are roughly parallel to one another, and that their velocities are of the same order, they do not represent the typical meteoritic condition, as heretofore defined. They rather illustrate the planetesimal phase of the meteoroidal condition.

The foregoing hypothesis of the origin of meteorites makes them but an incidental result of stellar and planetary action. Their genesis is wholly a secondary matter, and furnishes no ground for regarding meteorites as the parent material of great nebulæ or of stellar systems. The quantity of matter dispersed in this way is, by the terms of the hypothesis, limited to an extremely small part of the total mass of the system from which it is derived. It is therefore regarded rather as an incidental result of trivial importance than as a primary condition capable of generating great systems. This scattered matter is presumed to be picked up bit by bit by all the larger bodies, as is being done daily by the earth; and the maintenance of the supply requires only the disruption of small bodies to an extent equal to the trivial masses gathered in by the existing suns and planets. The exceedingly small amount of meteoritic material picked up by the earth is in harmony with this interpretation.

The hypothetical nature of this discussion of meteorites will be noted and due reserve in building other views upon it should be exercised, but the suggestions made in it may have some value in rounding out a consistent conception of the factors involved in the complex problem of which earth-genesis is a part, and may be helpful in distinguishing between competent generating factors and merely incidental by-products.

In conclusion, it may be remarked that the meteoritic condition seems most probably to be the product of incidental dispersion, and to be the source of merely incidental accretion by existing bodies, having neither great magnitude nor importance. It does not see

to represent a great generative method whereby s
evolved. Originated, by hypothesis, in dispersion,
gent in its own tendencies, passing into the gaseou
hand, or into the planetesimal on the other, or, es
depleted by contributing its constituents, one by on
and planets.

III. THE PLANETESIMAL HYPOTHESI

Under the typical form of the planetesimal hypoth
that the parent nebula of the solar system was form
small bodies, planetesimals, revolving about a cent
much as do the planets today. The evolution of
sisted in the aggregation of these innumerable small
fewer large ones; in other words, in a transition fro
a planetary system. The hypothesis, therefore, pos
mental change in the system of dynamics, after the
formed, but only an assemblage of the scattered ma
of dispersion of the material at the outset and thr
was maintained *by orbital revolution*, or, more clos
the centrifugal acceleration arising from revolution.
hypothesis by no means excludes gases from playi
parent nebula, or in its evolution, any more than it den
in the sun or the atmosphere to-day, but it assigns
a subordinate place in the evolution of the planetary
planetesimal condition had become established.

Subvarieties of the hypothesis.

Under the broad general conception that planets g
esimals, it is possible to entertain different views as t
origin of the planetesimal condition. That condition

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[1] This hypothesis has been gradually developed by the senior
during the past decade, with the very important advice and aid o
and other scientific friends. Partial expositions have been ma
societies at different times, and a somewhat extended stateme
Book No. 3, Carnegie Institution, 1905, pp. 208–253, but this is its
with illustrations. A statement from the standpoint of a mathe
and a master in celestial dynamics will be made by Dr. Moulton
work on astronomy.

growth of a gaseous spheroid of the Laplacian type, or it might possibly be developed from a meteoritic state under certain conditions, or it might arise from the mode of dispersion to which the nebula itself was due. This last is taken as the type case.

Planetesimal condition arising from a gaseous spheroid.—If the parent nebula were a gaseous spheroid, as assumed by Laplace, and were to detach material from its equatorial belt, molecule by molecule, rather than by rings, these molecules would probably become planetesimals instead of members of a true gaseous body. It is not the thought that these molecules would be thrown off directly into planetesimal orbits, because their initial paths would probably be ellipses that would bring them back to the point of departure; but that, by certain classes of collisions while in these elliptical orbits, they would be diverted into orbits that would not bring them again into collision with the parent spheroid. It is not of sufficient importance to this discussion to explain in detail the process by which this would be accomplished, but the ingenious student will readily work it out for himself. There is reason to believe that this method would really be almost the only systematic one by which a gaseous spheroid of the Laplacian type would detach material from its equatorial belt.

But granting that this be not true, and that an earth-moon gaseous ring was formed, as assumed in the Laplacian hypothesis, computation shows that its attractive power at any one point on its surface would be very low. If the present earth were converted into a solid ring, occupying its present orbit, it would have a diameter of about twenty-five miles, with its present average density. Computation is scarcely necessary to show that the gravity of this ring, at any point on its surface, would be very feeble; and it is obvious that this gravity must be greater than the gravity on the surface of the same matter when dispersed in the form of a gas by intense heat. Now the application of the kinetic theory of gases to such a ring, under the postulated temperature, forces the conviction that the molecules would have been so driven apart by mutual collision that they would have become essentially independent of one another, each revolving in its individual orbit, with only rare and incidental collisions. In other words, they would have become planetesimals controlled by the central mass, and not a gaseous aggregate controlled by its own gravity. They would, therefore, not have been concentrated by direct attraction, on the principles controlling a cooling g would have been subject to accretion, one by one, in th to be described.

Planetesimal condition arising from the meteoriti circumstances, meteorites might possibly be assembl that they would come to revolve in concentric orbits mon center of gravity, and thus assume a quasi-pl tion, in contradistinction to that of a typical swarm which each is habitually drawn toward the center, colli after the fashion of gaseous molecules, as conceived Darwin. The meteoroids that are formed by the disp such as constitute the belts that give rise to the Augu meteoric showers, are probably in the planetesimal collision-rebound condition, and are becoming more ar and individually independent, as time goes on.

Planetesimal condition arising from original neb The type view, however, assumes that the parent neb esimal organization from the outset. The conce radical departure from the gaseous conception of meteoritic conception of Lockyer, so far as funda and mode of evolution are concerned. In the followir special phase of this view will be adopted, partly for th ness and such clearness as the complexity of the sub and partly for the following reasons:

(1) *It postulates that form of nebula which is by far the spiral;*

(2) *This form of nebula gives a spectrum consistent u constitution, if, indeed, it does not directly imply such*

(3) *This form of nebula seems to possess the requisite and momenta;*

(4) *The special view of the origin of this form of ne that which is liable to happen, is simple in its basal even catastrophic as the genesis of a system can well be ass*

While this will be followed as the type view, le noted that the planetesimal doctrine of accretion does with this particular conception. As a first step in let us turn to the heavens for such light as existing upon their own origin and constitution.

The characteristics of present nebulæ.

So far as their constitution is now revealed by the spectroscope, nebulæ fall into two general classes, the one characterized by bright spectral lines, the other by a continuous spectrum.

1. **Free-molecular nebulæ.**—The first are usually said to be gaseous, but this not a sufficiently accurate designation. The bright lines of the spectrum can only be affirmed to indicate that the matter of the nebulæ is in a *free-molecular* condition. They do not certainly indicate whether (1) the molecules are in the collisional relations of gaseous molecules, or (2) are scattered widely, like the stars of heaven, so that collisions are rare and incidental, or (3) are moving on radiating or on parallel lines, or (4) are pursuing concentric orbits and are thus planetesimal in dynamic character. For the purposes of this discussion, where dynamic distinctions are important, these nebulæ may be designated, with due reserve, simply as *free-molecular nebulæ.* They often have a greenish cast from the predominance of green lines in their spectra, and are conveniently styled green nebulæ. The bright spectral lines indicate the dominance of hydrogen, helium, and an otherwise unknown element, or elements, provisionally called nebulium. There are occasionally a few other non-metallic elements, but *metals have not been detected.* Their constitution, as now determined, does not, therefore, fit them for the parentage of our earth, in which metals abound and in which hydrogen and helium are subordinate elements, while nebulium is unknown. The possibility of transmutation into suitable elements cannot, to be sure, be safely denied in these days of revolutionary discoveries. The class includes the "planetary," the "stellar," the "ring," and most of the irregular nebulæ.

Almost identical with the spectra of these nebulæ are the spectra developed in an early phase of the declining stages of the new stars that occasionally flash forth with sudden brilliancy and soon die away to obscurity or extinction, continuous spectra sometimes marking the later stages. While the origin of these "*Novæ*" is unknown, the conjecture that they are due to collision or to explosion has been entertained, and this conception has also been extended to the free-molecular class of nebulæ. By remote and uncertain speculation under the stimulus of recent revolutionary discoveries in dissociation, the violence of their assigned origin may be in some way correlated with extremely low molecular weights of their constitute their apparently elementary condition. It is a f fact that the early spectra of these new stars and t are closely similar to those of the "helium stars" an stars", which astronomers usually place in the first or in evolutionary classifications of the stars. There i ground, therefore, for linking together in genetic st the *Novæ*, and the helium-hydrogen-nebulium nebulæ, upon them provisionally, as primitive states. If ou *genesis of stars*, these would seem to point the way, s does at present; but our quest is the genesis of the *planets*, in one of which our study centers; and the ge is not necessarily and immediately connected with the Nebulous bodies composed of helium, hydrogen, and nebulium might, for aught science dare now affirm, into material of the complex terrestrial type; but t rather too bold for prudent use as a basal factor in hypothesis.

The forms of the helium-hydrogen-nebulium nebu more promising for planetary evolution, when their dy ties are considered. While observation has, as yet, de nothing as to their internal movements, their forms d the belief that they would, under known laws, evolv characterized by the peculiar distribution of mass which the solar system presents. For the present, nebulæ may be passed by in a search for the immedia earth.

2. **Aggregate-molecular (planetesimal?) nebulæ.**— of nebulæ give continuous spectra, and are convenient nebulæ. The continuous spectrum is interpreted to chief luminous material is in a liquid or solid state, or that the molecules are in an *aggregated* state, in disti free state of the previous class. As the liquid conditi a rather narrow range of temperature, and as this rang ent for different materials, it is improbable that any la nebula is in this state, and the whole may be conveni though solid, but in a finely divided condition. This seems necessary, for the volume of these nebulæ is of

and yet they appear to intercept but little light, and give no signs of great attractive power.

The dominant form of these nebulæ is the *spiral*, as determined by the late Professor Keeler,[1] and this form particularly characterizes the smaller nebulæ recently brought to knowledge by improved instruments and manipulative skill. These newly discovered nebulæ are estimated to number at least ten times the whole number previously known. From the superior number of spiral nebulæ it is a safe inference that their peculiar forms represent some prevalent process in celestial dynamics. That is, in itself, a reason why research should turn to them by preference for the origin of the present solar system.

Nothing is yet positively known of *the motions* of the parts of these spirals, for time enough has not yet elapsed since they were first sharply photographed to permit the requisite comparisons. Inferences from their remarkable forms are the only present resource. The accompanying photographic illustrations of some of the larger and more distinct forms will permit independent judgment as to the validity of these inferences (Figs. 12 to 21). To us their peculiar forms seem to imply that the spirals sprang from *a combined outward and rotatory movement*. The outward movement may have been already checked by the gravity of the central mass, and the rotatory motion be dominant at present, but their forms seem still to bear the impress of an outward movement. If the outward movement has ceased, or when it

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[1] The profoundly lamented death of Professor Keeler, just as he was beginning to reap the rich fruits of his skill and patience in nebular investigations, gives historical value to his latest statement of results, published about two months before his death.

"1. Many thousands of unrecorded nebulæ exist in the sky. A conservative estimate places the number within reach of the Crossley reflector at about 120,000. The number of nebulæ in our catalogues is but a small fraction of this.

"2. These nebulæ exhibit all gradations of apparent size from the great nebula in *Andromeda* down to an object which is hardly distinguishable from a faint star-disk.

"3. Most of these nebulæ have a spiral structure. . . .

"While I must leave to others an estimate of the importance of these conclusions, it seems to me that they have a very direct bearing on many, if not all, questions concerning the cosmogony. If, for example, the spiral is the form normally assumed by a contracting nebulous mass, the idea at once suggests itself that the solar system has been evolved from a spiral nebula, while the photographs show that the spiral nebula is not, as a rule, characterized by the simplicity attributed to the contrac ing mass in the nebular hypothesis. This is a question which has already been t up by Professor Chamberlin and Mr. Moulton of the University of Chicag trophys. Jour., June 1900, pp. 347, 348.

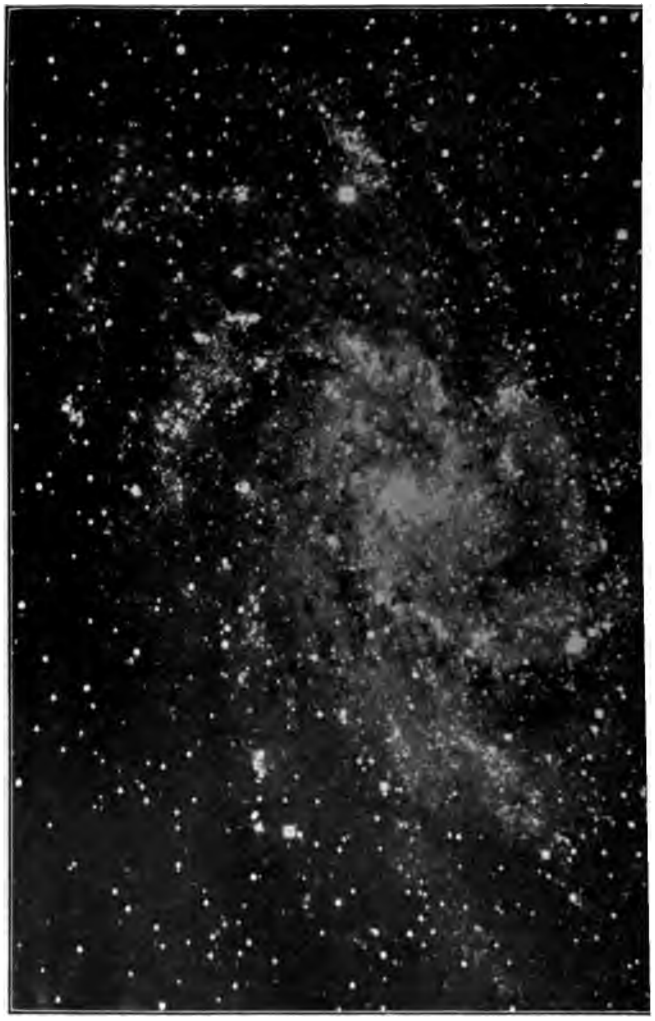

Fig. 12.—A very large, highly dispersed nebula, Messier 33, in th
the knots are very pronounced and the nebulous haze is irreg
It is interpreted as young, because the arms are not greatly c
lous haze has not become generally distributed. A successi
pulses seems to be indicated. Judged by the luminosity, th
in the nucleus is relatively small, and so the difference in the m
and inner parts is much less than in a system of the solar
lution is very slow. The distance is unknown, and hence the
known, but they are probably much greater than those of the s
is much uncertainty in judging of the mass by the luminosit
matter may have little luminosity and some may not be lu
central and denser portions are likely to be relatively more
dispersed portions. (Photo. by Ritchey, Yerkes Observatory.)

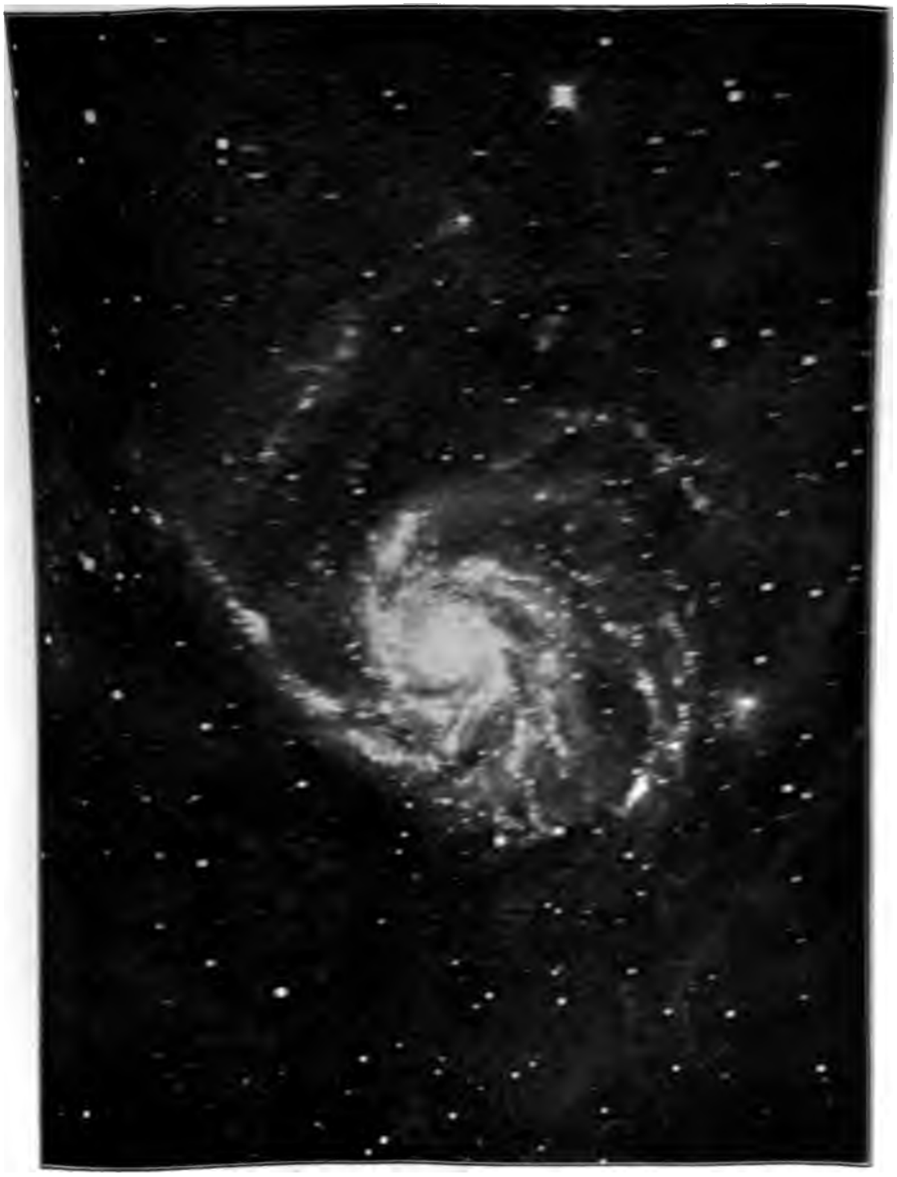

FIG. 13.—A spiral nebula in Ursa Major, Messier 101. The arms are much divided, which is assigned to a succession of expulsions at successive stages of approach. (Photo. by Ritchey, Yerkes Observatory.)

ceases, the rotatory movement must tend to wra
and more closely[1] and symmetrically, because
inner parts must be more rapid than those of
forms that seem to be the more mature appear
inner parts are coiled more closely and symmet

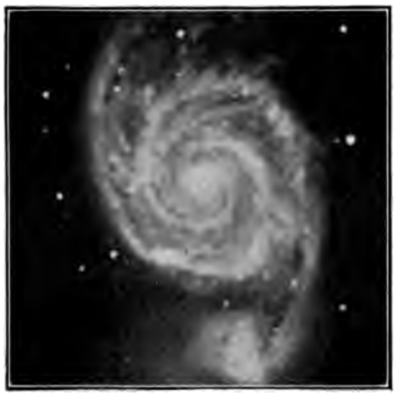

FIG. 14.

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FIG. 14.—A brilliant spiral nebula in Canes Venatici, Mess
long and has given relative exaggeration to the faint
apparently dense and relatively massive; the coiling
symmetrical in the inner parts, but departs from sym
A second nucleus is attached to the extremity of one a
as the representation of the disturbing star, it should pe
of colder, heavier material, much less subject to expulsiv
dispersed, and only slightly affected by rotating influen
the comet-like streamers of some of the knots and dens
true streamers, curved by motion, they imply an activ
the similar inference drawn from the coiled condition.
be interpreted as young, but as having advanced rapidl
because of its massive nucleus. (Photo. by Ritchey, Ye

FIG. 15.—A spiral nebula (Messier 61) in which the centra
the immediately surrounding portion diffuse and hazy,
retains its spiral distribution. The middle of the oute
tain most of the outlying matter, the distribution som
the solar system. The dimensions here are presumptivel
of the solar nebula, but this is not certainly known. (I
tory.)

parts. This is notable in Figs. 13 and 14. In t
in Canes Venatici (Fig. 14) there are curved str
of comets, stretching outward from some of th
If these are indeed streamers driven outward

---

[1] This does not mean that the matter is drawn toward t
the arms are stretched and more closely coiled.

curved by motion, as in the case of comets' tails, they testify very definitely to a rotatory movement.

A notable and seemingly very significant feature of these nebulæ is the presence of *two dominant arms* that arise from diametrically opposite sides of the nucleus, and curve concentrically away. No single-arm spiral of the watch-spring type has been found. There are often more than two arms in the outer part, and there is much irregularly dispersed matter, but even in the more scattered forms the dominance of two arms is discernible.

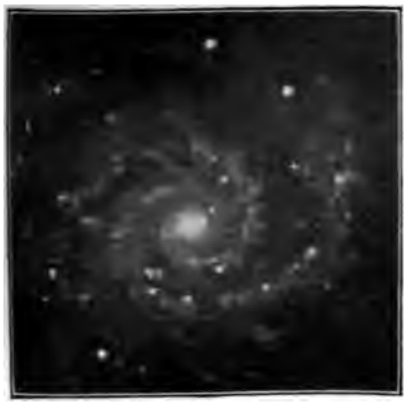

FIG. 16.

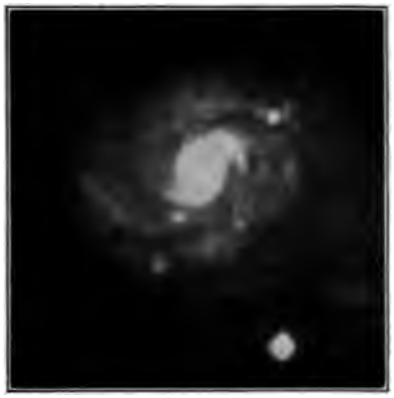

FIG. 17.

FIG. 16.—A typical spiral nebula in Piscium, Messier 74, with very symmetrical arms, pronounced nucleus and knots, and a relatively limited amount of nebulous haze. (Photo. from Lick Observatory.)

FIG. 17.—A suggestive nebula in Ceti, Messier 77, in which the proportions between the apparent masses of the central and the outlying parts is somewhat analogous to those assigned the solar nebula; so also are the proportions between the knots and the nebulous haze, and the number of the knots is also similar, but the volume of the central portion is disproportionately large. (Photo. from Lick Observatory.)

A second feature of note is the presence of numerous *nebulous knots* or partial concentrations on the arms, and more or less outside them. So, also, the more diffuse nebulous matter is unequally distributed, and in some of the forms, regarded as youngest, dark spots and lines emphasize the irregularity (see Fig. 12).

All these features go to show that these forms are controlled, not by the support of part on part, as in a continuous body, or in a mass gas, or even in a definite swarm of quasi-gaseous meteorites, b[illegible] some system of combi[illegible]netic energy and gravity which *perm*[illegible] *pendence of parts.* It is, therefore, conceived that solid or liquid particles which the continuous s revolve about the common center of gravity as planetoidal bodies. If this were certainly knowı these might be well called *planetesimal nebulæ.*

It is clear from the tenuity of these nebulæ, as s of the spiral, that they are thin and disk-like, and this to be so in the case illustrated in Fig. 18, which is see slender ellipse shown in Fig. 19 probably represents a wise, but this is not certain. In their disk-like sha

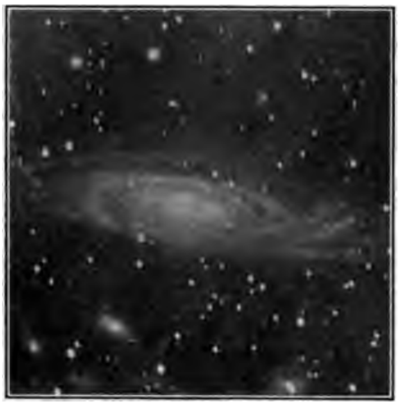

FIG. 18.

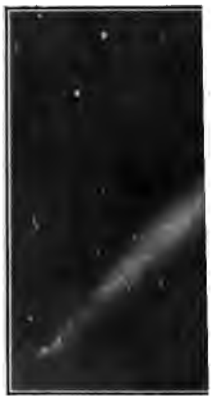

FIG. 19

FIG. 18.—A spiral nebula in Pegasi (HI 53), seen obliquely, sh form. (Photo. from Lick Observatory.)

FIG. 19.—An elliptical nebula (HV 41), interpreted uncertainly seen from a point in its own plane. (Photo. from Lick Obse

conform to the mode of distribution of matter in t Within the area of their disks also, the distributio it is in the solar system—a fact too much overlooked predilection for symmetry, under the influence of Laplacian conception.

If these nebulæ are composed of minute aggregat volving as planetesimals about the nebular centers, *the outer parts is necessarily high* in proportion to tl portions, and in this essential particular they meet th of the difficulties that confront the Laplacian hypoth

All of the spiral nebulæ of our illustrations have vastly transcend those of the solar system, and they cannot be taken as precise examples of the solar evolution. Because of these vast dimensions and of the probable feebleness of control of the central mass, which often appears to be itself quite tenuous, a rapid motion cannot will be assigned to the arms. Seen from the immense distances at which the nebulæ seem to be placed—no parallax having been as yet detected—changes of position must necessarily be slow in revealing themselves to observation. It is to be hoped, however, that the presen rapid progress in the perfection of instruments and of skill will s

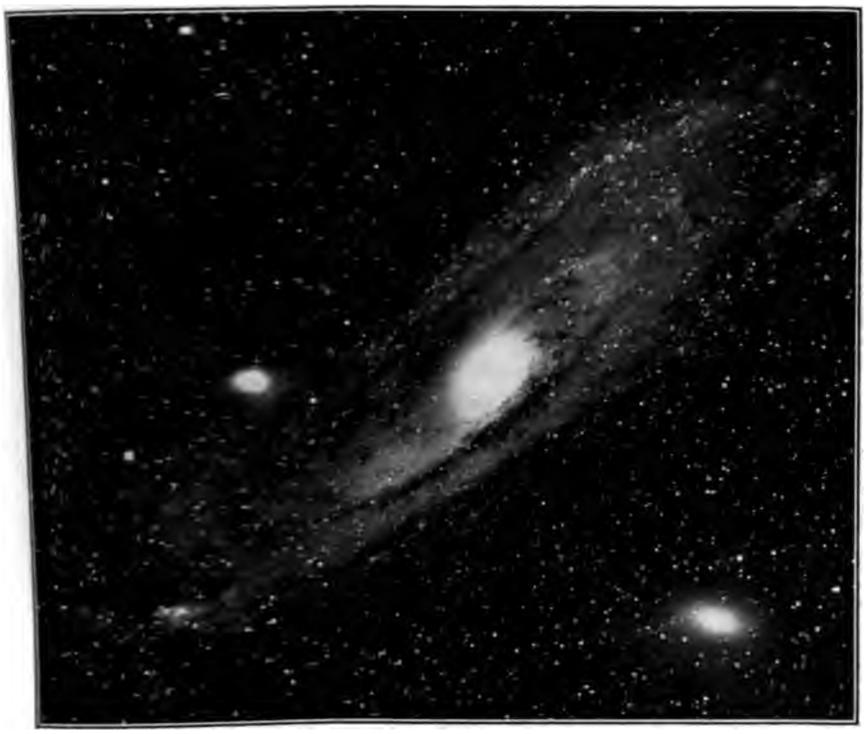

FIG. 20.—The great nebula in Andromeda, seen, apparently, obliquely; the greatest of the spiral nebulæ. The nucleus is highly preponderant and spheroidal; the knots are less pronounced than in the preceding, and nebulous haze is more abundant relatively. The spectrum is continuous, with some dark lines, implying that the central nucleus is akin to the sun. No parallax has been determined, but the distance is inferred to be great and the dimensions immense, as many small stars *appear* to be this side the nebula. This nebula has sometimes been suspected to be in reality a stellar system outside our own. Two smaller spheroidal nebulæ are shown which may or may not be connected genetically with the great one. Photo. by Ritchey, Yerkes Observatory.)

bring within the reach of successful study some
nebulæ that represent more nearly, in mass and p

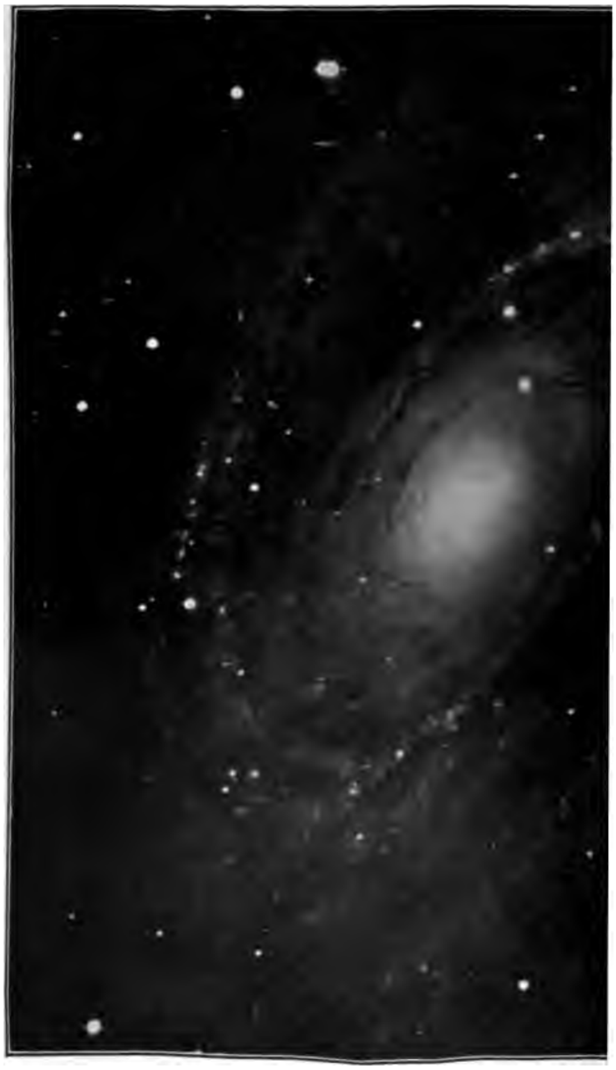

FIG. 21.—A spiral nebula in Ursa Major, Messier 18, showing
mass, with symmetrical arms, well coiled. Form and
those assigned to the parent solar nebula. Interpreted
in evolution. (Photo. from Lick Observatory.)

system, and that some of these will be found suf
mit an early determination of their motions.

While awaiting, for how long we cannot tell, such positive determination, it may contribute to clearness of view, even if it shall fail to be an anticipation of the real fact, to definitely picture the possible origin of the supposed nebula that grew into the present solar system.

The hypothetical origin of the solar nebula.

An implied ancestral system.—The inference that a spiral nebula is formed by a combined outward and rotatory movement implies a preëxisting body that embraced the whole mass. In harmony with this, an ancestral solar system is postulated—a system perhaps in no essential respect different from the present one. Our hypothesis does not, therefore, concern itself with the primary origin of the sun or of the stars, or with the ulterior questions of cosmic evolution. It confines itself to a supposed episode of the sun's history, in which the present family of planets had its origin, and in the initiation of which a possible previous family may have been dispersed; but no affirmation is made relative to the last point. With some partiality perhaps, this episode may be regarded as geologic, since it specially concerns the birth of the planet of which alone we have intimate knowledge.

The question of adequacy of energy.—To this conception of an ancestral sun, with an undefined antecedent history as a star, question will arise at once as to a sufficiency of energy for the sun's maintenance through such a prolonged history. It has been strongly urged during the past half-century, by very eminent physicists, that the resources of energy assignable for the maintenance of the sun's heat and light could, at best, be barely sufficient for the geological and biological demands of the earth's known history, even when these are most conservatively estimated. How much less then can they be sufficient for an antecedent history of unknown duration! This objection is based on the assumption that the sun's heat and light are derived *almost wholly* from self-compression, as urged by Helmholtz. That self-compression is a potent source of heat is not questioned, but the Helmholtzian theory takes no account of sub-molecular and sub-atomic sources of energy. The transcendent potency of these sources of energy has been for some time suspected,[1] and is

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[1] The following was written in 1899 before experimental demonstration had b realized: "Without questioning its correctness, is it safe to assume that the Helmholtzian hypothesis of the heat of the sun is a complete theory? Is present kr

now being revealed by refined physical research. T
energies displayed by radio-active substances are d
initial demonstration of immeasurable energies resider
of matter and in the constitution of the sidereal sys
tent for its maintenance for unassignable periods. It
therefore, in the light of recent revelations in physic
coveries in the constitution of the stars and the stel
there is any sufficient reason for setting narrow lim
the sun. It seems more in accord with recent advance
place the compressional theory of the sun's heat in
the earlier chemical and meteoritic theories, as tr
tory, but as only partial and inadequate. The one
above all other things, which the progress of researcl
recognition is the immensity of the energy of the u
energy only a small fraction is usually apparent to us, c
it is *chiefly in a state of equilibrium*, and only becom
its equilibrium is disturbed.

There seem to be no sufficient grounds, therefor
to assume an ancestral solar system, the center of whic
of the present sun. This involves the further quite rea

relative to the behavior of matter under such extraordinary
in the interior of the sun sufficiently exhaustive to warrant the asser
nized sources of heat reside there? What the internal constit
may be is yet an open question. It is not improbable that they
zations, and the seats of enormous energies. Certainly, no ca
affirm either that the atoms are really elementary, or that ther
up in them energies of the first order of magnitude. No cau
probably venture to assert that the component atomecules, to use
may not have energies of rotation, revolution, position, and be
ble in kind and proportion to those of a planetary system. I
ably feel prepared to affirm or deny that the extraordinary con
in the center of the sun may not set free a portion of this energy.
theory takes no cognizance of latent and occluded energies of
atomic nature. A ton of ice and a ton of water at a like dista
of the system are accounted equivalents, though they differ nota
of their energies. The familiar latent and chemical energies ar
gible quantities compared with the enormous resources that re
But is it quite safe to assume that this is true of the unknown
in the internal constitution of the atoms? Are we quite sure we
bottom of the sources of energy and are able to measure even rougl
On Lord Kelvin's Address on the Age of the Earth as an Abode
hamberlin, Science, Vol. IX, June 30, and Vol. X, July 7, 18

tion that the sidereal system has had a very prolonged history, and that the ancestral sun played its part in it as the solar system does now.

The contingencies of stellar collision.—There are probably at least 100,000,000 suns in the present sidereal galaxy, and these are moving, so far as now determined, in various directions and at various velocities, much like the molecules of an exceedingly tenuous gas. Besides these suns, there is possibly even a larger number of dark bodies associated with them as extinct suns, planets, planetoids, and satellites. It would be strange, therefore, if there were not occasional collisions, especially in the more crowded portions, as in the Milky Way, however rare these might be relatively. It is in or near the Milky Way that new stars appear, and also there that the free-molecular nebulæ chiefly abound. This coincidence of distribution obviously does not, of itself, carry so broad a conclusion as that the new stars and the free-molecular nebulæ necessarily arise from collision; but the contingency of collision, when such a multitude of bodies are moving in such diverse ways, can scarcely be questioned, notwithstanding the vast distances involved and the consequent smallness of the contingency for a given body within a limited time. But to the phenomena of collision no appeal is here made, except as a part of a consistent conception of the whole group of associated phenomena.

The contingencies of close approach.—If there are contingencies of actual collision between stars, there must be much larger possibilities of their *close approach* to one another and to dark bodies. Celestial bodies possess velocities inherited from past states, and velocities due to the existing attraction of other bodies, so that close approach is assignable in part to the crossing of predetermined paths, and in part to the mutual attraction of the great bodies themselves. The contingencies of collision and of close approach arising from these two factors follow different laws. Considering inherited motions alone, the contingencies of collision are greatest when the velocities are highest and the bodies thickest. The contingencies of close approach by mutual gravity are greatest when previously acquired velocities are least and conflicting attractions are fewest and feeblest. It is obvious that as the inherited velocities approach infinity, collision approaches infinite frequency, while gravitational deflection approacl the infinitesimal. On the other hand, if inherited velocities reduced to zero, gravitation would draw a finite grou together. When both factors are present, *relative* *lision and disruptive approach* lies between the two extr ical inquiry [1] leads to the interesting conclusion that mo velocities lie near that happy medium that gives few from which the inference is drawn that *a selective pr* *most of the bodies of dangerously high and dangerously l* *has left those possessed of the relatively safe intermediate v*

If all stellar motions are like the known motions, a stars constitute a system by themselves, a uniform be maintained in all parts of the stars' courses, nor c prevail in all portions of the system. The velocities on the average, when a star is traversing the interior o the contingencies that attend high velocities must be The inherited velocities must be presumed to be lowe borders of the system, where the constituent bodies re their outward excursions and turn back, under the gravi to again traverse it. This at least seems the most ter of the movements of the members of the stellar sys as a finite group of bodies possessed of the known m trolled by the known forces. The alternative concepti extension of stars is beyond treatment here. On the therefore, mutual attraction is assumed to be relatively than in the central portions. But, as some residual moti previous excursions is even there retained, and as a part inevitably tangential, *close approaches* rather than co disturbing contingencies indicated.

In this outer portion also, the paths assigned the *nearly parallel*, because all are approximately parallel t the stellar sphere at their turning-points, and hence energies as the bodies possess oppose less resistance to t the bodies to one another, for it is only when the motions or transverse directions that their kinetic energies re approach.

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[1] Made by the senior author in coöperation with F. R. Moulton thal.

[2] There are, however, a number of stars with great enough veloci beyond the visible system, even after allowing liberally for dark bodie

In harmony with this conception is the fact that the known spiral nebulæ are distributed on the sides of the supposed stellar disk or flat spheroid of which the Milky Way is the assigned equatorial girdle. If spiral nebulæ occur on the outer border of the Milky Way, as our view seems to imply that they should, they are doubtless beyond the limits of distinct vision.

Whatever may be the value of this particular view of the causes of close approach, it is a consistent, if not necessary, assumption that, in a multitudinous stellar system characterized by diverse rates of motion in diverse directions, close approaches of suns to one another are contingencies likely to be realized in fact.

The special consequences of close approach.—Our present sun shoots out protuberances to heights of many thousands of miles, at velocities ranging up to 300 miles and more per second. If it were not for the retarding influence of the immense solar atmosphere, some of these outshoots would doubtless project portions of themselves to the outer limits of the present system, and perhaps, in some cases, quite beyond it, for the observed velocities sometimes closely approach the controlling limit of the sun's gravity, if they do not actually reach it.[1] This illustrates the enormous explosive elasticity resident in the sun's interior. The expansive potency of this prodigious elasticity is held in restraint by the equally prodigious power of the sun's gravity.

If, with these potent forces thus nearly balanced, the sun closely approaches another sun, or body of like magnitude, possibly one several times the mass of the sun, since the sun is regarded as a small star, the gravity which restrains this enormous elastic power will be *reduced along the line of mutual attraction*, on the principle made familiar in the tides. At the same time the pressure transverse to this line of relief will be increased. Such localized relief and intensified pressure must bring into action corresponding portions of the sun's elastic potency, resulting in protuberances of corresponding mass and high velocity.

Dynamic considerations seem to make it clear that the sun might even thus be wholly disrupted, if the body to whic were much superior to it in mass and the approach Roche long ago demonstrated that the differential large body upon a smaller one revolving about it, w disrupt it at an appreciable distance, as previously In a body whose elasticity nearly matches its gravity, i that the Roche limit should be actually invaded phenomena of a high order of intensity and magni place. A more distant approach would suffice.

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[1] A body falling from infinity to the sun's surface, and thus acquiring the maximum velocity which the sun's attraction can give to it, would strike the sun's surface at 382 miles per second, which is technically known as "the velocity from infinity," or the "parabolic velocity," since a body shot from the sun with this velocity would take a parabolic path and never return. This, therefore, represents the maximum power of control of the sun, and the velocity of some protuberances is nearly equal to it.

Exceptional protuberances developed on opposite si proach.—According to the well-known tidal principle, protuberances would rise from opposite sides, and herei explanation of the prevalence of two diametrically the spiral nebulæ.

The demands on protuberant action not severe planets and their satellites, all together, amount to hundredth part of the mass of the system. Simpl required planetary matter, the protuberances need small fraction of the ancestral sun; but some cons the projected matter must probably have been gat the sun, and some part may possibly have been p the control of the system. Making allowances for bo the proportion of the sun's mass necessarily involved ances is still very small. Apparently one or two per mass would amply suffice.

The acquisition of rotatory motion.—The protub pothesis, would be thrust out as the sun and the p swinging about their common center of gravity in cu sharp, and at velocities more or less prodigious, ac relative distances. That protuberance which was sh toward the star would be drawn forward by the star i its movement, with a power inversely proportional to distance. The protuberance shot in the opposite dir attracted by the star also, but owing to its greater increasing distance, in a very greatly less degree, in acc same law. The sun at an intermediate distance wo in an intermediate degree. With reference to the su two protuberances would move in opposite directions, a relative to it would be revolutionary. To follow out even approximately the actual motions of the sun and the protuberances in a given case of this kind is extremely difficult and laborious. It is obvious, furthermore, that in any given instance a succession of protuberances following one another at different stages of approach must probably have taken place, and hence the formation of a nebula presents a series of such extremely difficult problems. Dr. Moulton has worked out the selected case of two opposite protuberances, in which the mass of the passing star is assumed to be equal to that of the sun, and the protuberances are assumed to be shot out to twice the star's perihelion distance (Fig. 22). It is further obvious upon consideration that the number of possible cases that might arise from the varying ratios of the masses and from the varying distances of their approach, is very large, and that immense labor is involved in covering the whole ground and finding out what cases are applicable to the problem of the solar nebula, but in the course of the series now being worked out under the direction of Dr. Moulton, it is hoped that a close approximation to the solar nebula may be found, a hope which seems to be warranted by the results thus far obtained. Analytical considerations have seemed to show that if the disturbing star were equal to or more massive than the sun, and were to pass very near to it, a large portion of the sun would be dispersed with great velocity, and the resulting nebulæ would probably resemble those immensely expanded ones which are chiefly represented in the foregoing illustrations. A more distant approach in which the protuberances are small relative to the mass of the sun seems to more in consonance with the demands of the solar problem. It

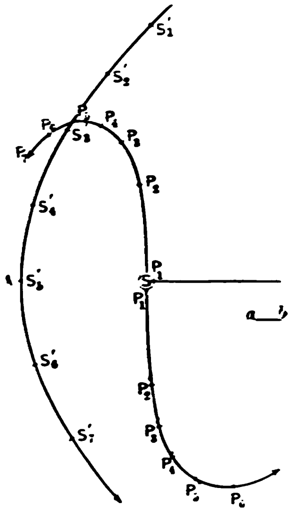

FIG. 22.—Diagram illustrating the courses pursued by particles, P and P', shot out from the sun, S, on opposite sides under the disturbing influence of a passing star, S', when at the position S_1'. The successive positions of the disturbing star are indicated by S_1', S_2' . . . S_7', assumed at successive time-intervals. When S' was at the position S_1', the particles P and P' were shot out from S with velocities such that if not disturbed they would have reached to distances twice AS. P_2 . . . P_7 and P_2' . . . P_7' are the successive positions assumed by these particles at the successive times. a–b is the acceleration at unit distance. (After F. R. Moulton.)

observed that the curves in Fig. 22 are of the general
case requires.

The distribution of specific gravities.—The distal
protuberances would obviously be formed from the
tions of the sun, while the later portions of the eject
proximal parts of the arms would doubtless come m
depths, and hence probably contain more molecules
gravity. In this seems to lie a better basis for explai
dinary lightness of the outer planets, and the high
of the inner ones, than in the separation, from the ex
surface of a gaseous spheroid, of successive rings w
equaled the one-thousandth part of the original nebu

Successive partial outbursts.—It seems consisten
ditions of the case to assume that the protuberanc
of a succession of more or less irregular outbursts,
sun, in its swift whirl around the controlling star, wa
affected by the latter's differential attraction; and
tuberances would be directed in somewhat changi
would be pulsatory in character, resulting in rather irre
what divided arms, and in a knotty distribution of th
along the arms. These knots must probably be more
from inequalities of projection.

The result a spiral nebula.—It is thus conceived that
having two dominant arms on opposite sides, each kno
lar pulsations, and rotatory, the knots probably als
attended by subordinate knots and whirls, together
scattering of the larger part of the mass in irregular
would arise from the simple event of a close approac

Theoretical diagram of the solar nebula.—On the b
going considerations, there is herewith presented a the
tion of the solar nebula (Fig. 23). The purpose of t
definite conception of the favored phase of the plane
esis—not to enforce its correctness or acceptance.
trary, the frank concreteness it gives to the conce
criticism, and invites modification by future study.

The passage of the molecules from the free to the agg
The ejected matter, at the outset, must have been in th
state, since by the terms of the hypothesis it aro

ous body; but the vast dispersion and the enormous surface exposed doubtless quickly reduced the more refractory portions to the liquid and solid state, attended by some degree of aggregation into small accretions; hence the continuous spectrum which this class of nebulæ present.

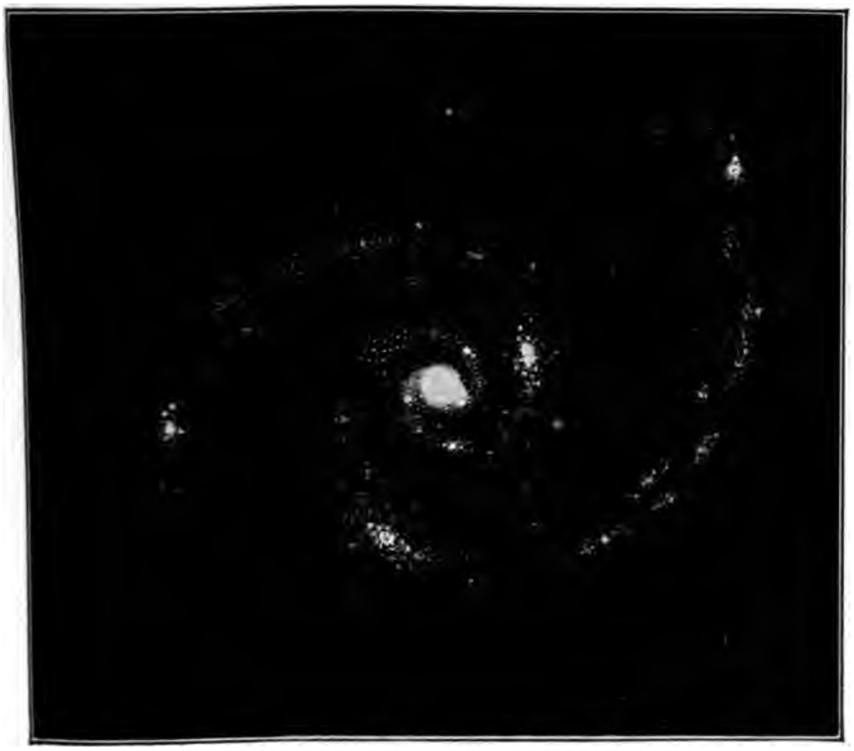

Fig 23.—Theoretical restoration of the parent nebula of the solar system. The nuclei of the several planets may be indentified by their distances from the center. The dimensions of the inner parts are made disproportionately large.

Nebular luminescence.—The problem of the luminescence of nebulæ is confessedly a puzzling one. There is little ground for assigning general incandescence to matter so obviously scattered and tenuous, and possessed of such enormous radiating surface. The assignment of the light to collisions of meteorites, as has been done by Lockyer, encounters both dynamic and spectroscopic difficulties. The recent discoveries of the luminescent properties of radio-active matter, and of its power to awaken luminescence in other matter, offers hope of a solution. The fact that these properties are not ne ent on heat greatly relieves the stress of the proble radio-active material there might be in the matte nebulous form would, by such dispersion, be set fre whatever other matter was subject to its excitation w free to receive the exciting influence.

The solution of the problem may, however, lie lines. At present it seems more probable that the lu from some agency that acts at low temperatures than ent on heat, and hence objections to a planetesimal the ground of low temperature cannot have much for

The assigned nebular origin not vital.—Whethe mode of origin of the spiral nebula just sketched be t vital to the planetesimal hypothesis. It is offered as picture and as a contribution to the natural demand mode of genesis. It is only vital to the planetesim here developed, that the scattered nebular mater around the central mass in elliptical orbits, and t be sufficiently implied by the forms of the spiral neb ing the question of their origin. It is true that their interpreted as implying streams of *in-running* matte courses, but a system of dynamics, on known princi ent with known conditions, has never been worked process, so far as we are aware, and it is not evident

As a basis for following onward the evolution, tw tions only are necessary, (1) that the nebular matter a finely divided solid or liquid condition, as the con implies, and (2) that the particles of this scattered m elliptical orbits about the central mass.

The evolution of the nebula into planet

The three essential factors.—The knotty spiral fo gives ground for recognizing three factors as the chi the evolution into a planetary system, (1) the central the sun), (2) the knots (to become the nuclei of the the diffuse nebulous matter (to be added to the nu planets or to be added to the sun). Fitting the concep case of the solar nebula, the present distribution of warrant the assumptions that (1) the central mass was overwhelmingly large, (2) the knots were quite irregular in size and very unequal in distance from the center, and (3) the nebulous part was small relative to the central mass, and probably large relative to the knots. Reasons for the last conclusion will be given later.

The attractive powers of the knots and their limitations.—It is assumed that the masses of matter in the knots were sufficiently large to hold themselves together in spite of the differential attraction of the central mass; otherwise they would soon have been scattered. They seem to have successfully maintained themselves in nebulæ that appear to have undergone some notable degree of evolution, as for example the knots shown near the large central nucleus in Fig. 13.

On the other hand, it is presumed that the gravity of the more tenuous nebular matter was insufficient to aggregate it directly, in the presence of the central attraction, for this portion seems to show a progressive tendency to a more general diffusion, as may be seen by comparing the cloudy flocculent distribution of the nebulous matter in Fig. 12, whose form implies that it is young in evolution, with the more diffuse distribution in Figs. 15, 17, 18, and 21, whose central coilings imply more advanced states of evolution. The planetesimals of this diffuse nebulous portion are, therefore, assumed to be controlled essentially by the gravitation of the main mass, and to revolve in individual orbits about it.

The irregularity of the forms of the knots seems to imply that their organization is also planetesimal, though the larger ones may be able to hold gases also. The direction of revolution of these knots is supposed to be usually the same as that of the rotation of the nebula as a whole, but subject to local and special influences that might lead to important variations.

The knots the planetary nuclei.—The knots of the solar nebula are regarded as the nuclei about which gathered the planetesimals to form the future planets; not that all such nuclei necessarily retained their independence and grew to planets, but that no planet probably developed except from such a nucleus. The figures already presented Figs. 12–21) show clusters of knots and aggregates of irregular form susceptible of development into complex planetary systems, such as th large planets and their families of satellites. The earth-moon sy is assigned to a couplet of companion nuclei of quite unequal s

The sizes of the nuclear masses.—If the present pl
from these nebular nuclei, the greatness of their gr
by the smallness of the primitive nuclear masses.
such accretion is a matter of geologic interest, for it
related to many dynamical questions of the eart
There are two considerations that bear upon the si
nuclei.

1. There is a certain inherent and necessary limi
of scattered or tenuous bodies in the presence of mor
The principle involved is one of vital importance in th
ary evolution. Within the field of the effective attr
nant body like the sun, or the ancestral nebular ce
exercise differential gravitative control over a limi
known, technically, as the "sphere of activity." Th
earth, with its *present mass*, reaches out about 6
the earth has grown at all, its primitive sphere of c
been smaller than this. The earth nucleus could,
have embraced such matter as lay within this li
the original knot could be supposed to have extended
the outlying portion would have been drawn away b
into independent planetesimals, and must have bee
it became a part of the earth, by some other means t
tion. The moon controls, as against the attraction o
present distance, a sphere whose radius is about 2
considerably less than 25,000 miles as against the j
the earth and sun. Its primitive nucleus, if it has g
confined to smaller dimensions. Attenuated nuclei
cannot, therefore, be supposed to maintain themsel
in the fields of attraction dominated by larger bodies
subject to the dispersive effects of their own molec
addition to the competitive gravity of dominant b
narrower limits, and below a certain mass are inev
In such a system as ours, gases must, for the most
themselves to the dominant bodies or be scattere
planetesimals. None of the smaller knots of the so
probably have been gaseous in any large measure. Ga
attached to and occluded in the aggregated or solid p

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[1] "The Spheres of Activity of the Planets," Moulton, Pop. Ast

may have been held in a free gaseous state in the interiors of the larger nuclei. The sun is of course presumed to have been gaseous throughout the evolution.

2. Quite a definite indication of the size of the nuclei of the planets may perhaps be deduced from the very remarkable fact that Phobos, the inner satellite of Mars, revolves around the planet in *less than one-third* of the time of the planet's rotation, and from the analogous fact that the little bodies which make up the inner part of the inner ring of Saturn revolve about that planet in a little more than *one-half* the time of the planet's rotation.[1] These are exceedingly troublesome facts from the view-point of the Laplacian hypothesis, for under it the contraction of these planets, after they had shed their secondaries, should have greatly accelerated their rotations, and these should have become much shorter than the revolutions of the secondaries. Before Moulton's citation of the second case, an attempt was made to explain the case of Phobos by a supposed tidal retardation of the planet's rotation, but the Saturnian case appears to render this explanation incompetent.[2]

Under the hypothesis of growth from a nucleus by the addition of planetesimals, the rotations of the planets were dependent largely on the special phases of the impacts of the infalling planetesimals, and no necessary relations between the rotation of a planet and the revolution of its satellite are assignable. But if this be neglected, and the rotation-period of the planetary nucleus be assumed to have been originally the same as the revolution-period of the satellites' nucleus, *the growth of the mass of the planet must have drawn the satellite nearer to itself, and shortened the time of its revolution.*

If the whole of the periodic difference between Mars and Phobos be due to this cause, the growth of the nucleus of Mars is deducible from it. Under this view, the matter of the rings of Saturn may have been satellite nuclei at the outset, and have been drawn within the Roche limit by the growth of Saturn, and then disintegrated by tidal action and distributed into the ring form. All other satellites should, under this view, have been drawn towards their primaries during the growth of the latter, and this may be factor in their evolutionary history.

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[1] For a discussion of these phenomena, see "An Attempt to Test the Nebular Hypothesis by an Appeal to the Laws of Mechanics," Moulton, Astrophys. Jour 1900. p. 109.

[2] See Moulton's discussion, loc. cit., pp. 109, 110.

The concurrent bearings of these two consider harmony with what might be gathered independ parison of the apparent amounts of matter in the the amounts in the nebular haze. It will, theref our further study, that the nuclei constituted only the mass of the grown planets. The fraction w *proportionately* for the small planets than for t the power of growth probably rose with increased ratio. In the case of the asteroids and satellites t have been large.

The mode of accretion.

The nature of the planetesimal motions.—Th planetesimals to the nuclei to form the planets is to conjunctions in the course of their orbital mot gravitation, except as gravitation was the fundam orbital motions. The nature of the primary moti first consideration. The combination of outward a to which the formation of the nebula is assigned, w form to the whole, at the outset, is believed to h individual planetesimal *an elliptical orbit about the* recurring to our hypothesis of the origin of the spira the tangential impulses had been duly balanced, ci have resulted; but neither theory nor observation ma this was often the case. The inevitable inequalitie ponents should give ellipses varying in eccentricity tion in their relations. As, however, both the outwa components sprang from the same source—the grav induced by the approach to a massive star—there that they would not be extremely unequal, and that t tricities, though large, would not be excessive. Thi with the forms of the spiral nebulæ. These do n symmetrical configurations of the strictly circuloid elliptical ones, with irregular elements. The de present almost circular configuration of the solar s a broadly elliptical, somewhat irregular, spiral con an evolution in the direction of circularity and symmetry, in the course of the aggregation of the scattered matter. The method will be presently indicated.

The part played by ellipticity of orbit.—The ellipticity of the orbits is the very factor that furnishes the assigned agency of aggregation, and of this progressive evolution towards circularity and symmetry. In the initial stages, the ellipses of the nuclei and of the innumerable planetesimals were, by reason of their common origin, rudely concentric. They were, to be sure, more or less discordant in form and in attitude from the effects of unequal projection, of differential expansion of the solar matter when set free by projection, and of the collisions of the constituent planetesimals; but all of this was subordinate to a general concentric arrangement of the elliptical paths. Under the laws of celestial mechanics, these paths must have been constantly modified by the different attractions of the different portions of the nebula. The axes of the orbits must have shifted, the attitudes of their orbital planes must have varied, and their eccentricities must have been modified. It will suffice to consider the shifting of the major axes of the orbits, technically "the motion of the line of apsides," as that is the most vital factor in the process of aggregation.

So long as the major axes of the orbits were essentially parallel to one another, as *A* and *B* in Fig. 24, the bodies would remain apart and aggregation be prevented; but when they became shifted differentially to the positions *A'* and *B'*, the orbits would touch, and conjunction be possible, if the orbital planes were appropriately related to one another.

The shifting of the lines of apsides is in constant progress in the present system, and must of necessity take place in any such system, as the laws of celestial mechanics require it. The shifting is differential and subject to various perturbations, involving alternate movement forward and backward, but the average result is an advance.[1] At present the line of apsides of quickest revolution is that of Saturn, which completes its circuit in 67,000 years, roundly speaking, while that of Neptune requires 540,000 years, and that of the earth a little more than 100,000 years.[2] In the course of time, the major axis of each orbit is thrown athwart that of its neighbors, and whenever the

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[1] Celestial Mechanics, Moulton, p. 245.

[2] Young's General Astronomy, p. 313.

longer axis of the smaller orbit is equal to the shorte
orbit, and the planes of the orbits are properly r
rendered contingent. Actual collision is dependen
the bodies reaching the crossing of their paths at th
planes of the planetary orbits now lie near to on
presumed always to have done so. These planes, tho

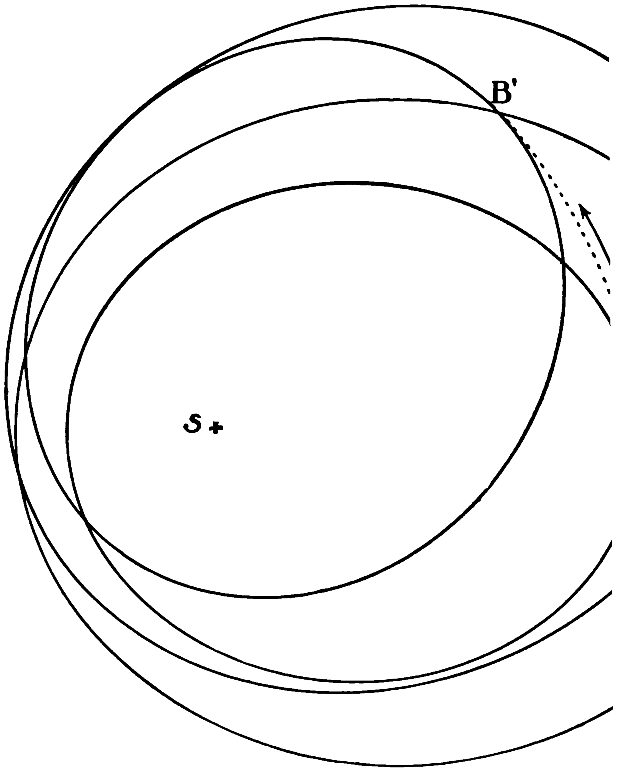

FIG. 24.—Diagram of a smaller orbit, *B*, lying within and par
A, both having a common focus, *S*; the absence of the con
is obvious so long as they retain this relation even approxin
shift differentially to the positions *A'* and *B'*, conjunction is
planes are properly related. If the orbit *A* were to shift
effect would be the same.

the orbits, intersect one another, and the lines of int
ing so that in time all assignable intersections are
these conditions, the mechanics of such a system fu
contingencies for collisions between the planetesima
if sufficient time be granted.

The collisions of isolated planetesimals with one another may be neglected, for it is uncertain whether the planetesimals would rebound from one another or would unite; probably the former when they were highly elastic, and the latter when inelastic; and probably much would also depend on their velocities and their modes of impact; but in any case, the result would only affect the size and number of the planetesimals. The important consideration is the impact of the isolated planetesimals upon the planetary nuclei. In this case the usual result must apparently be the capture of the planetesimals by the nuclei, and with each capture, the power of further capture would be augmented.

The evolution of circularity.—When two bodies in concentric elliptical orbits unite, their conjoined mass must move in an orbit that is intermediate between the two previous orbits, and this new orbit, in all cases investigated, is less eccentric than one of the previous orbits, and may be less eccentric than both, as illustrated in Figs. 25 and 26. While a mathematical demonstration that this is universally true is possible, the illustrations suffice to show that it holds for most normal cases falling within the problem in hand. It follows that the union of an indefinite number of orbits progressively reduces the resulting orbit toward circularity. In application, there arises the obvious corollary that the planets which have grown most have, in general, lost most of their primitive eccentricity and those that have grown least most nearly represent the original eccentricity. The significant application of this to the planets of the solar system will appear later.

The time involved.—When the slowness of the motion of the line of apsides, and the only partial coincidence of the planes of the orbits, at any one time, are duly considered, it is evident that the contingencies of collision for the entire number of planetesimals will be spread over a protracted period, and that collisions can succeed one another rapidly only as the immensity of the possible number insures this. Individually, the chances of collision are remote and infrequent; but as the numbers involved at the outset were prodigious, the impacts upon a given nucleus in a given time may have been numerous. In the nature of the case, the impacts must have declined in frequency after the greater number of planetesimals had been gathered i the nucleus.

The bearings of the rate of infall on temperatu
accretion is a matter of radical geologic importanc
in some measure, the most critical feature of the wh
lem; for the rate of accretion determines whether
perature on the surface of the growing body will be h
surface temperature is not determined by the total h

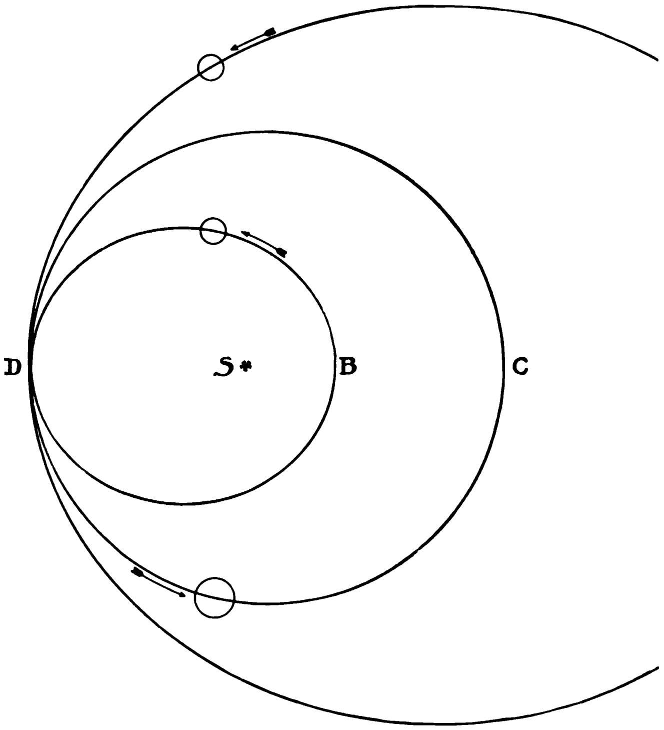

Fig. 25.—Diagram to illustrate the tendency toward circularity
the uniting bodies have concentric positions. The two bo
orbits *A* and *B*, and uniting at *D*, necessarily take an interm
an obvious advance toward circularity. In less simple and s
result is less obvious, but it would be of the same order in all
problem in hand.

the collisions, but by *the heat produced in a given tim*
is determined by *the frequency and force of the collision*
If the succession of collisions on a given square mile is
to generate heat beyond the concurrent radiation from
a high average temperature for the whole cannot
ever great the sum total of heat generated in the co

is to be noted that the heat generated after a solid nucleus was developed must have been superficial, and hence readily radiated away. While the nuclei remained assemblages of small bodies, perhaps gaseous in part in the larger ones, planetesimals from without may have penetrated to the interior, and there developed heat not so readily lost. But this state is only assignable to the early stages of growth.

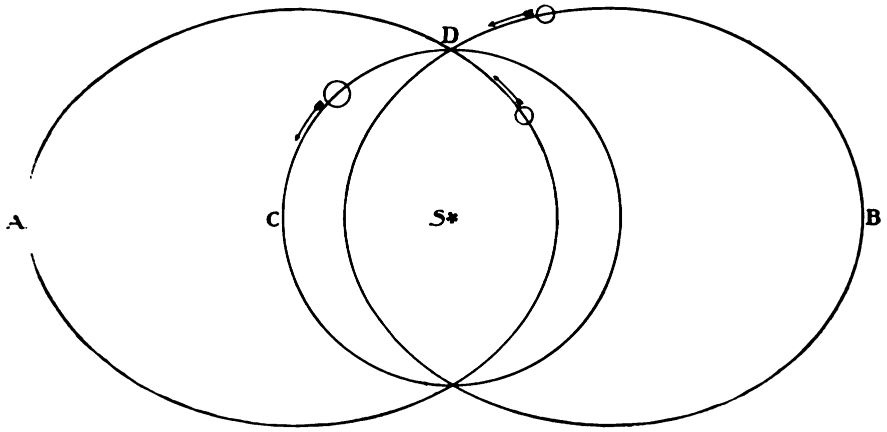

FIG. 26.—Diagram to illustrate the evolution of circularity where the orbits of the uniting bodies are as far as possible from having concentric positions. The bodies in the orbits *A* and *B*, meeting and uniting at *D*, necessarily take an intermediate orbit *C*, which is obviously more circular than either. In less symmetrical cases, the tendency would be of the same order.

The collisions all overtakes.—A further consideration bearing upon the critical subject of temperature is the manner of collision. Since all the planetesimals and planetary nuclei were revolving *in the same direction* about the solar mass, the collisions were all overtakes, and could have been violent only to the extent of their differences of orbital velocities, modified by their mutual attractions. Since their orbits were elliptical, their velocities varied considerably in different portions of their paths, and hence overtake collisions of considerable velocity were possible. These velocities were, however, of a much lower order than the average velocities of meteoritic collisions. Many of the overtakes must obviously have been due to differences of velocity barely sufficient to bring about an overtake. When the average mildness of impact is considered, in connection with the intervals between impacts at a given spot, the conviction can scarcely be avoided that *the surface temperature would not necessarily have been high.* It seems probable that it would have been moderate throughout of aggregation, and certainly so in the declining sta

The bearing of the mode of accretion on the dire rotation.—We have now reached a point where the tested. It happens to be a point where all hypoth have been supposed to be fatally at fault. The cr in *the direction of rotation* which would result from t matter in this way. At the same time, the bearing broadens, for this vital question of direction of rot all forms of aggregation of independent bodies movin the common center of a system. For example, if the solar system be supposed to start with a gaseou Laplacian type, and to proceed in the manner postu until the planetary rings were formed, and if then the molecules, resulting from mutual impact, carried gravitative control of the rings so that they were volved independently around the central mass, t their aggregation would be as much subject to the t the special hypothesis now under consideration. S of forming definite rings, the molecules were separat posed gaseous spheroid, one by one, as seems mo separation by rings, their aggregation is equally open fatal weakness. So indeed is the concentration of assemblage of discrete matter in which the individ aggregates revolve independently.

The lion in the way—and he appears to have tur pilgrim—is as follows: In a ring revolving *as a unit,* rings are supposed to have done, the outer part mov inner part; and so, if a planetary ring parts at its w gathers into a globe about the center of its cross-sect *forward,* as shown in Fig. 27. If, on the other hand the ring revolve *independently,* the inner ones must the outer ones, and if they collect about the middle held that the rotation must be *retrograde,* as illustrat

By way of exception, to meet the singular case Neptune, it has been suggested that if the matter

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[1] For ampler statements of this difficulty, see Faye, "Sur l pp. 165, 270–281, 1896. Also Young's General Astronomy, pp.

rings, revolving as units, happened to collect about some point other than the center of the cross-section, the foregoing conclusions would not hold, but if the matter were drawn together by gravity simply, as usually supposed under the Laplacian hypothesis, it is not evident why it should not collect about the middle part.

Now as matter of fact, the six inner planets and their satellites rotate *forward*. The satellites of Uranus revolve backward in a plane inclined 82.2° to the ecliptic; those of Neptune also revolve backward, in a plane inclined 34.5° to the ecliptic. The rotations of these planets themselves have not been determined. These exceptional inclinations and revolutions have been interpreted as very oblique or partially overturned revolutions. Accepting the foregoing premises, the prevalence of direct rotation has been regarded as strongly confirmatory of an origin from gaseous rings rotating as units, and as strongly adverse to accretion from bodies revolving independently. The force of this line of reasoning has apparently been felt to be so strong as to be essentially fatal to the latter conception. It, therefore, requires critical consideration.

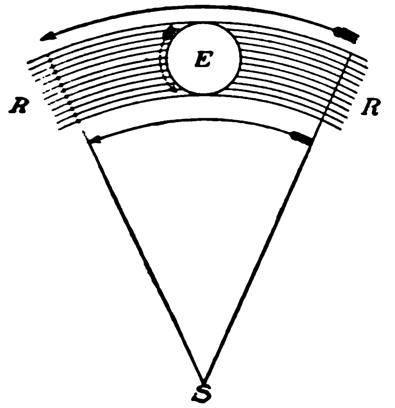

FIG. 27.

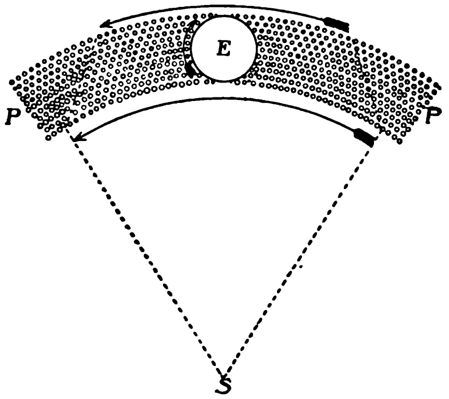

FIG. 28.

FIG. 27.—*RR* represents a ring of gas moving as a unit and hence the outer portion the faster. If converted into a spheroid, *E*, centrally located, the rotation is forward, as shown by the arrow.

FIG. 28.—*PP* represents a belt of planetesimals revolving concentrically about the center, *S*. If these collect about the central point of the belt into a spheroid, *E*, by the enlargement of the inner orbits or the reduction of the outer ones, the concentric arrangement remaining, the rotation will be retrograde, as shown by the arrow.

The reasoning is good *for the special case cited*, that of a symmetrical

ring of perfectly circular form, in which the inner b
with the outer ones, are supposed to strike their inner
about this delicate adjustment systematically, the orb
closely concentric, and the inner ones must be enlarg
ones be reduced, so that they will approach concent
the sum of the semi-diameters of the bodies to be un
esimals were arranged in strictly circular concentric
separated from one another at the distances the ca
mechanics by which they could be brought into this
collision consecutively is not evident, and has not
pointed out. It is certain that their union into a sph
be, by any means, the simple direct and rapid pro
sumed.[1] On consideration it will be seen that the
is a very special and quite artificial one, for all the p
orbits are *elliptical*, and are by no means strictly conce

It becomes evident, on studious consideration, t
which could probably arise from any actual antecede
esimals *must have had elliptical orbits;* for even if th
gaseous ring of the Laplacian type, the rebounds o
as they collided and separated, must have given rise t
elliptical orbits. Even in this case the eccentricities
have been many million times the sum of the semi-
particles. In the case of planetesimals derived from
the orbits are necessarily assigned very notable eccer
these cases, the most available mode of aggregation,
practicable one, lies *in the crossing of the orbits* broug
constant shifting of their major axes, as already set

Now a planetesimal in a smaller elliptical orbit ca
tact with a planetary nucleus in a larger orbit *only*
less *aphelion* portion of its orbit coincides with a more
portion of the larger orbit of the nucleus, and a planet
orbit can come into contact with a planetary nucleus
only when a more or less *perihelion* portion of its orb
a more or less *aphelion* portion of the nucleus orbit, as
To illustrate by a pronounced case, a planetesimal, *P*, in

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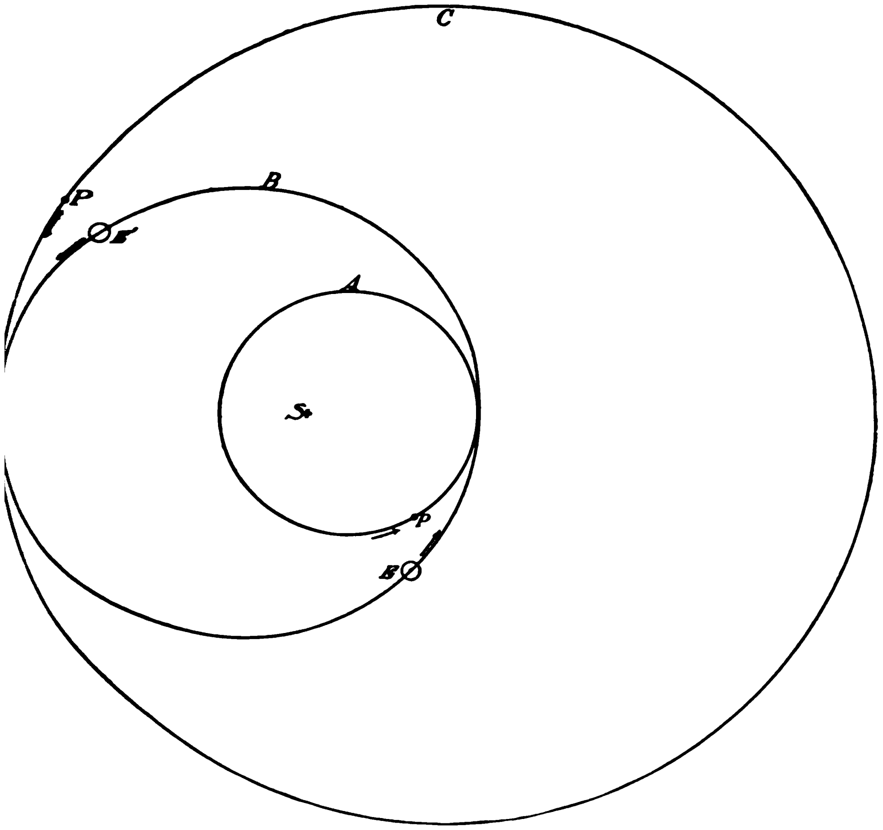
[1] This has been discussed mathematically by Moulton, "An
Nebular Hypothesis by an Appeal to the Laws of Dynamics," A
XI, pp. [illegible], 1900.



. 29.—Diagram illustrating the condition under which collisions may take place in elliptical orbits of the planetary type. *S* represents the solar mass at the center of the system, *E* the planetary nucleus, *B* its orbit, *p* a planetesimal in the orbit *A*, smaller than *B*, and *P* a planetesimal in the orbit *C*, larger than *B*. The case has been so chosen as to represent at once the smallest and the argest orbits of typical eccentricity that can come into contact with the orbit of he planetary nucleus. The minimum extreme is found when the aphelion point f the small ellipse *A* coincides with the perihelion point of the orbit of the lanetary nucleus *B*. In no other position can the orbit *A* touch the orbit *B*. he maximum extreme is found where the aphelion point of *B* coincides with e perihelion point of *C*. In no other position can these orbits touch. Be- reen these limiting phases, represented by the orbits *A* and *C*, there are an definite number of possible planetesimal orbits that might cut the orbit *B*, t in all cases, except where the orbits were like *B*, conjunction could arise ly when *a more or less* aphelion portion of an inner orbit touched or crossed a re or less perihelion portion of *B*. If the orbits were equal, the velocities at crossings would be equal and the rotating effects would be *nil*, or neutralized, if they were nearly equal, the difference would be slight, so that the effective s are those of the extreme classes represented. Further explanation is given e text.

29), can only come into contact with a planetary nucleu
B, at the point where it is farthest from the sun, or it
So likewise a planetesimal, *P*, in the large orbit, *C*, ca
contact with the planetary nucleus, *E*, at the point where
comes nearest to the sun, its perihelion. In the first c
nucleus is at its perihelion; in the second, at its aph
chosen as limiting cases; between them there are innu
intermediate ones. The two selected are the most
results because the differences in the velocities are gr
they may be regarded as embracing the whole and a

Now the vital point lies in the fact that, *at the poin*
body in the *smaller* orbit is moving *slower* than the
orbit, though *on the average* it moves the faster. F
planetesimal, *P*, at the points where alone it may c
with the nucleus, *E*, is moving slower than *E*. If coll
at all, *E* must overtake *P*. This may be demonstrated
of celestial mechanics,[1] but it may also be readily see
for at the point of contact *E* has a velocity suffic
farther away from the sun through the larger orbit *B*
in the orbit *A*, from deficiency of velocity, falls b
sun. At the points where the planetesimal, *P*, in the
alone come into collision with the nucleus, *E*, the case
the planetesimal, *P*, has the greater velocity, and mu
there is any collision at all.

The varying effects of the impacts on the rotati
in the outer orbit were always to strike the outside of
inner orbit, as in the ideal cases illustrated, the impact
to forward rotation; but the orbits may cross one anot
in the inner orbit may have passed the crossing befor
by the body in the outer orbit, and so the inertia
body may be felt on the *outer* side of the nucleus and
retrograde rotation. It is, therefore, necessary to
two opposite classes of effects, and to estimate the r
of all probable collisions. It will be seen at once t
influence must be far less in magnitude than the sum
impacts, for the opposing classes neutralize one ano

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[1] An elegant method of determining the velocity of a body
elliptical orbit is given on p. 139 of Moulton's Celestial Mecha

the resulting rotation is likely to be relatively low, though the total force of impact be great. It is further evident that the result might have varied considerably in the different planets, and this is in concordance with the varying rotations actually presented by the several planets.

It is still further obvious, on inspection, that the greatest differences of velocity, and hence the greatest rotatory effects, must occur in the extreme or limiting cases of collision that occur at the perihelion and aphelion points of the nucleus' orbit; for, where the orbits have more nearly the same dimensions and the crossings are at points intermediate between these extremes, the differences of velocity are less and the rotatory effects less, whatever their phases.

The average or residual effects of collisions in the limiting cases may be gathered from the case represented at the left in Fig. 30, in which planetesimals in small orbits are *overtaken* by the nucleus near its perihelion point, and from the case at the right in which the planetesimals in the large orbit *overtake* the nucleus near its aphelion point. By inspecting the figure, it will be seen that the areas which represent the possibilities of overtake favorable to forward rotation exceed those favorable to backward rotation. This holds true on the assumption of an equable distribution of planetesimals, which may fairly be assumed as the average fact, but not necessarily as always the fact; and hence the conclusion is not rigorous, and a backward rotation is not impossible. From the nature of the case, a varying rotation for the several planets is more probable than a nearly uniform one.

It is also obvious that the impacts on the right and left sides of a growing nucleus, as well as those on the outer and inner sides, might be unequal, and hence *obliquity* of axis of rotation of varying kinds and degrees might arise. As the solar system presents these variations, the method of accretion here postulated seems to lend itself happily to the requirements of the case.

The order in which the contingencies of collision come into play—There is a supplementary factor arising from the order in which the contingency of collision arises. If a planetesimal is subject to two equal contingencies of collision with the planetary nucleus, of opposite effect, it is obvious that the one which it first encounters has a better chance of realization than the other; for if the first is realized, the second loses its chance. Now by reference to Fig. 31 it will be seen

is dependent on the eccentricity of its own orbit, and
tricities of the orbits of the planetesimals it gathers in

Competitive nuclei and selective dominance.—It i
there may have been two or more nuclei originally w
zone. If one of these was notably smaller than the
be picked up by the latter, the same as if it were a plan
of equal size might perhaps unite, though this would
take place. Two nuclei in nearly the same zone must
same belt of planetesimals, and must mutually inte
another's growth. If there were little difference in thei
outset, that one which was best spaced out from the nuc
ing zones would be likely to become dominant by s
for it would have a better feeding-ground, so to speak.
that was smaller at the outset, if well separated from la
might become the dominant one by a better growth.

If there were originally many nuclei of minor ma
were much scattered, especially if the planes of their
verse, the dominance of any one might be avoided, and
of all result, as in the case of the asteroids.

The shifting of orbits.—It seems to be a sure infere
process of growth, the nucleus must have *worked towa*
the zone from which it gathered, as a consequence of th
ing on the richer side. For example, if more planetesim
up on orbits smaller than its own, its orbit must hav
as a mechanical result of the accretion, for a new or
the union of two bodies, is intermediate between th
orbits, and hence smaller than the larger one. If mo
were picked up on the outer side, the orbit of the nu
grown larger. The nucleus, therefore, must have wor
center of the richer feeding-ground, or in average c
original distribution, toward the ground not preyed
nuclei.

The spacing-out of the planets.—The foregoing
toward a selection of nuclei for dominance, and to an au
out of the successful nuclei. This process, if our hyp
should find verification in the actual distribution of
be an explanation of it. This distribution should co
eccentricities of the nuclei, modified by the proporti

mals of larger and smaller orbits gathered in by them. Assuming these to have been somewhat equable, the planetary distribution should be roughly proportional to the eccentricities of the nuclear orbits. As a basis for inspection, let it be supposed that the collecting zone of each planet reaches half-way to its neighbor on either hand; and let the eccentricity of the orbit of each nucleus be such that the nucleus itself shall sweep its whole collecting zone, which is more than the case absolutely requires. The following are the eccentricities so derived, compared with present eccentricities:

	Assigned Eccentricity.	Present Eccentricity.
Nucleus of Mercury	.25 ±	.2
Venus	.21	.006
Earth	.20	.017
Mars	.28	.093
Asteroids (mean)	.33	.38 } and less; mean about .15
Jupiter	.336	.048
Saturn	.366	.056
Uranus	.37	.046
Neptune	.38 ±	.009

There being no known planet outside of Neptune, the method can only be applied to it by an arbitrary assumption regarding its outside collecting area. It may be reasonably assumed that the nucleus of Neptune represented the head of the protuberance, so to speak, and that its accretion was essentially all on the inner side, which would draw its orbit inward, according to the principle above stated. This may account for its anomalous spacing out. There being no known planet inside Mercury, the eccentricity assigned it is also in a measure arbitrary.

With these qualifications, it will be seen that the assigned eccentricities are quite harmonious, and on the whole they indicate a progressively greater original eccentricity from within outward. By comparison with the existing eccentricities, it will be seen that the assigned original ones are much the more consistent. The reason for this, under our hypothesis, is close at hand. According to the principle of evolution from eccentricity toward circularity, stated above, the greater the

accretion, the greater the progress toward circularity.
somewhat by the perturbations which the planets creat
orbits, and by the special conditions of aggregation, t
tially true. For the large planets that have dominat
zones and presumably swept them thoroughly, the re
tricity are subequal. For the very small bodies that
but little, *the eccentricities remain large,* for the g
example, the eccentricity of Mercury, the smallest
remains more than twice that of any other planet.
smallest in size, comes next in eccentricity among t
the asteroids, that probably grew but little, have hig
a rule. Their orbits have doubtless been not a little
great influence of their powerful neighbor Jupiter,
application of so general a law as the one under consid
made to the details of their orbits; but the tenor of
suggestive. The highest eccentricity, .38, is as high as
tricity assigned to the original nuclei of the planets.
oids whose diameters are fairly well known, the half
and presumably have grown most, have orbits less ecc
cent. than the half that are smaller, and presumably
Of the orbital elements of 278 asteroids examined, th
lowest inclination to the common plane of the system,
ated for accretion, have eccentricities 21.9 per cent.
greater inclination. The orbits of Neptune and Ven
ally circular, the former perhaps on account of its o
and mode of accretion, as previously suggested, the
not obvious. Rigorously consistent results cannot t
such antecedents as are postulated in a case of this k
of consistency noted is perhaps to be regarded as much
than the departures from it. If this view of the s
planets be entertained, a rational law may be substitu
numerical formulation, known as Bode's law, viz.,
has been derived from a fairly consistent variation
eccentricities of the planetesimals and nuclei of the
which the outer were symmetrically greater than the inn

SUMMARY.

The planetesimal hypothesis thus assumes that the solar system was derived from a nebula of the most common type, the spiral, and that the matter of this parent nebula was in a finely divided solid or liquid state before aggregation, in harmony with the continuous spectra of spiral nebulæ. It regards the knots of the nebula as the nuclei of the future planets, and the nebulous haze as matter to be added to these nuclei to form the planets. It assumes that both the knots and the particles of the nebulous haze moved about the central mass in elliptical orbits of considerable, but not excessive, eccentricity. It postulates a simple mode of origin of the nebula connected with the not improbable event of a close approach of the ancestral sun to another large body, but the main hypothesis is not dependent on this postulate.

It assigns the gathering-in of the planetesimals to the crossing of the elliptical orbits in the course of their inevitable shiftings. Out of this process and its antecedents, it develops consistent views of the requisite distribution of mass and momentum, of the spacing out of the planets, of their directions of rotation, of their variations of mass, of their varying densities, and of other peculiarities.

It deduces a relatively slow growth of the earth, with a rising internal temperature developed in the central parts and creeping outward. With such a mode of growth, the stages of the earth's early history necessarily depart widely from those postulated by the Laplacian and the meteoritic hypotheses. These stages now claim our attention.

CHAPTER II.

THE HYPOTHETICAL STAGES LEADING UP TO TH

THE hypotheses of the earth's genesis having no the several stages of evolution that led up to the legible record of Archean times claim attention. as yet hypothetical, and the views presented are t with appropriate reserve. The study of these stage imperative, for during them the broader phases of the were brought into action, the essential features of were determined, and even the salient lines of its r out; and these have been perpetuated, in their gra the present time. Since these dominant characters w of the preceding history, they are to be interpreted the forming earth is thought to have followed the g with cooling as its great event, or (2) to have grown with increasing heat and gravity as its leading fe than these two lines of development seems to req sideration at present, for, however the genetic proces ably glided into the one or the other of these alterna the era was reached which gave to the earth its final f therefore, to outline in succession (I) the stages o under the gaseo-molten hypothesis, as commonly (II) a modification of these stages designed to raised by recent investigations, and (III) the accretionary hypothesis.

I. STAGES UNDER THE COMMON FORM OF THE (LAPLACIAN) HYPOTHESIS.

The hypothetical stages arising from the Lap nowhere been stated more definitely and succinctly t Dana,[1] and his synopsis is here introduced as a ty the general conceptions that have been entertained by the majority of geologists during the past century.

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[1] Manual of Geology, 4th edition, pp. 440, 44

"I. The *Astral* æon, as it has been called, or that of the fluid globe having a heavy vaporous envelope, containing the future water of the globe or its dissociated elements, and other heavy vapors or gases.

II. The *Azoic* æon. Without life.

1. The *Lithic Era:* commencing with the earth a solid globe, or at least solid at the surface; the temperature at the beginning above 2500° F.; the atmosphere still containing all the water of the globe (amounting to 200 atmospheres, according to Mallet, 1880), all the carbonic acid now in limestone and that corresponding to the carbon now in carbonaceous substances and organic substances (probably 50 atmospheres), all the oxygen since shut up in the rocks by oxidation, as well as that of the atmosphere and of organic tissues. The time when lateral pressure for crustal disturbance and orographic work was begun; when 'statical metamorphism,' or that dependent on heat of a statical source,—the earth's mass and the vapors about it,—began.
2. The *Oceanic Era:* commencing with the waters condensed into an ocean over the earth, or in an oceanic depression, with finally some emerging lands,—the temperature perhaps about 500° F., if the atmospheric pressure was still 50 atmospheres. The first of tides and the beginning of the retardation of the earth's rotation. Oceanic waves and currents and embryo rivers begin work about the emerged and emerging lands; the large excess of carbonic acid and oxygen in the air and water a source of rock-destruction; before the close of the era, the formation of limestones and iron-carbonate by chemical methods, removing carbonic acid from the air and so commencing its purification; the accumulation of sediments without immediate crystallization or metamorphism, and thereby the beginning of the earth's *supercrust.*

III. The *Archæozoic* æon. Life in its lowest forms in existence.

1. *The Era of the First Plants:* Algæ, and later of aquatic Fungi (Bacteria), commencing with the mean temperature of the ocean at possibly 150° F., since plants *now* live in waters up to and even above 180° F. Limestones formed from vegetable secretions, and silica deposits from silica secretions; iron carbonate, and perhaps iron oxides formed through the aid of the carbonic acid of the atmosphere and water; large sedimentary accumulations, where conditions favored, thickening the supercrust.
2. *The Era of the First Animal Life:* mean temperature at the beginning probably about 115° F., and at the end 90° F., or lower; limestones and silica deposits formed from animal secretions; deposits of iron-carbonate and iron-oxides continued; large sedimentary accumulations."

DIFFICULTIES ENCOUNTERED BY THE GASEO-MOLTE

Quite apart from the question of its general tr sources of serious dissatisfaction with the preceding v earth-stages have grown out of recent investigations, from failure to find any great basal formation bearin characters of an original crust; and the other, from relative to the prodigious atmosphere postulated.

1. *Evidence Relative to an Original Cru*

The theory of a molten earth carries the presu liquid mass arranged itself in concentric layers accor cific gravities of the constituents, if convection was n to prevent this. As the granitoids constitute the igneous rocks, their molten magma has been, very cons to the outer zone of the molten earth, while the magm neutral and basic rocks have been assigned to low conception was long ago set forth definitely by Durc lated an outer zone of rock derived from an "acid lower zone derived from a "basic magma."[1]

If, however, it be assumed that convection was too mit such concentric arrangement of liquid layers, t an intimate mixture of material must be substituted entiated layers, but the outer zone of rock must pr been homogeneous in the larger sense, for the conc *nent* areas of lighter rock in one region, and heavier at the same time and in the same horizon, is inco principles of hydrostatic equilibrium.

The theoretical crust a universal identifiable subst case, a characteristic surface of lava, either sensi or homogeneously mixed, and in approximate hydros should have constituted the material which solidified crust. This crust should, therefore, be a univers a distinctive character and susceptible of definite specially complete state of crystallization, of the seems to be a necessary attribute of a rock formed from a molten globe, except at the very surface, for the process of cooling must have been very slow, and the conditions for the growth of the crystals most propitious. The primitive formation should hence be of the most massive and declared holocrystalline type. Its distinctive character could scarcely be disguised beyond recognition by any probable katamorphism at a later date.

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[1] A clear statement of this logical view is given in Haughton' p. 3, to which is added a translation of Durocher's notable e petrology, in which the doctrine is elaborated.

The limitations of pyroclastic concealment of the crust.—No very large amount of scoriaceous and fragmental material can be assumed to have been heaped upon the original crust consistently with the hypothesis *in the form above stated;* for the assumption that the primitive atmosphere contained all the future water of the hydrosphere leaves no appreciable explosive agency in the molten globe to produce such material. The atmospheric and hydrospheric constituents, by the terms of the hypothesis, had either never condensed, or had been thoroughly boiled out of the white-hot mass. This is not an undue forcing of the mere phrasing of the hypothesis, for not a few familiar doctrines and working conceptions have been built upon the assumed exclusion of the hydrospheric and atmospheric constituents from the primitive rocks. The permanent concealment of the original crust under pyroclastic material cannot, therefore, consistently be assumed without modifying the hypothesis, for many thousand feet have been eroded from the surface of the oldest known areas.

The adverse bearing of recent discoveries.—Until recently, the great granitoid areas of the Archean series were thought to meet very fairly the theoretical requirements of the case; but it has been discovered in no less than five of the regions most critically studied, that many of these great granitoid masses are *intrusive,* and that they have been forced into rocks that were formed *on the surface* by lava outflows, volcanic fragmentation, or surface sedimentation. This significant discovery was made almost contemporaneously by geologists of Canada, the United States, Great Britain, Scandinavia, and Finland. While such an intrusive nature has not yet been proved for all the great granitoid masses of all Archean areas, the presumption now lies in that direction. The new interpretation thus reduces to an unknown, if not a vanishing quantity, the area of massive crystalline rock that can, with plausibility, be referred to the supposed original crust. Bu' the theoretical necessity for a large area of such rocks, if the molt hypothesis in this form is to be retained, has, at the sa more imperative with progressive investigation; for it all the vast series of sediments must have been derived f: crust and from such extrusions as have since come from it is becoming more and more evident that the origin: main portion of this material was the present land area ate borders. There is now no satisfactory evidence reversal of continental and oceanic areas, as was onc postulated. Abysmal deposits do not appear in the co: if one or two equivocal cases be set aside; and if abys not been added to the continents, continental areas ca sunk to abysmal depths, without destroying the critical sea to the land which seem to have been constantly mail is now, therefore, little or no plausible ground for supp abysmal portions of the crust were thrust up into higl ported there till great sedimentary series were deriv and then withdrawn to abysmal depths again. This a: not be pushed so far as to shut out mutual encroachm sions of *shallow* sea on land—which have been numerc changes in the relations of the deep basins and the cc forms; but it is probably quite safe to conclude that now buried beneath the sea, and not reckoned in the are greater in amount than any sediments that may hav from portions of the primitive land areas now buried b in other words, it is probably quite safe to assume that a derivative material as is now represented by the knc has come from the present land areas. There shoulc large areas of the original crust now occupying the su other areas lying beneath the sedimentary series in such accessible incidentally here and there. If the trend of : gation shall follow the present tendency, and exclude rocks of the Archean areas from the original crust, the in its original form, will have lost its observational supp

2. *Atmospheric Difficulties.*

The second point of growing dissatisfaction is a cc preceding one, for both spring from the assumption tl pheric and hydrospheric gases were e[illegible]d from the mc is on this ground that the primitive atmosphere is held to have been vast, hot, and heavy, and to have contained all the water of the globe, all the carbonic acid now in limestone, and that corresponding to the carbon now in carbonaceous deposits and in organic substances, all the oxygen since shut up in the rocks by oxidation, as well as that of the atmosphere and of organic tissues (p. 83). The assumption back of this seems to be that heat always promotes gaseous expulsion, and if so, the separation of the gases from the extremely hot molten rock should certainly have become most complete in the white-hot primitive globe. Under this view, absorption, rather than expulsion, should have been the rule in all later and colder states. This fundamental conception has been widely entertained, and has found familiar expression in certain volcanic hypotheses, in the supposed absorption of a former atmosphere and hydrosphere of the moon into that body, and in well-known prophecies of a similar doom for the envelopes of the earth.

The adverse evidence of early life.—The more the physiological functions and adaptations of the early life are compared with those of modern life, the more nearly identical they appear to be, and the more scant has become the basis for postulating profoundly different atmospheric and thermal conditions in early times. This observation is not confined to the discovery of air-breathing animals far back in geologic history, when a prohibitive excess of carbon dioxide should, theoretically, have still remained in the air, but relates as well to various adaptations found in nearly all forms of life, plants not less than animals. For example, the xerophytic organs of some plants that lived in the later half of the Paleozoic era are perhaps as irreconcilable with a vast hot vaporous atmosphere, overcharged with carbon dioxide and water-vapor, as is the presence of the flying insects with their extremely active organizations.

Incongruities on the physical side.—An atmosphere so heavily surcharged with carbon dioxide and water-vapor must have been rich in heat-absorbing power, and should have given a very warm, equable climate to the earth, as has been rightly assumed. Warm equable climates did indeed prevail in a *portion* of the earlier history of the earth, as also in the later; but the investigations of the past two decades in India, Australia, and South Africa have forced the recognition of extensive glaciation *on the very border of the tropics*, at a period as

early as the closing Paleozoic. Evidences of glaciation
Europe, and also in China in about 30° N. Lat., at or
the Cambrian, has recently been presented. Less strik
not less significant, is the occurrence in the early Paleo
salt and gypsum beds in rather high latitudes. These
imply severe and protracted aridity, and such aridity,
north of the 30° belt, is not readily reconcilable wi
equalizing atmospheric envelope.

There seem, therefore, to have been, in Paleozoic
same alternations of very uniform with very diversifi
marked the Mesozoic and Cenozoic eras; in other wo
tions of climate seem to have been of much the same
the known eras. The hypothesis of an enormous orig
suffering gradual depletion finds, therefore, but scan
support in a critical study of either the biological or
tory of the earth.

II. A MODIFICATION OF THE PRECEDIN

Can the gaseo-molten hypothesis be modified to
culties? The especially troublesome phases of the
from the assumption that the atmospheric and hydros
kept out or forced out of the hot molten globe, and
vast atmospheric envelope. If amendment be possibl
rently consist in assuming that lavas, *however hot,*
quantities of gaseous constituents which may be
Existing lavas bring to the surface great volumes of
They are disposed to discharge these, however, for t
under usual surface conditions; but the limits of thi
not yet well understood; indeed, the whole subject o
and retention of gases in molten rock is imperfectly
not inconsistent, however, with present knowledge to
molten globe of rock, arising from vaporized rock-s
retain large quantities of the atmospheric gases so lon
in the liquid state, and part with them only when it
admissible to go even further, and assume that muc
pheric material might remain occluded in the solid
gelation, since igneous rocks now contain notable quanti

making these assumptions, it may be held that during the molten state the gases were not fully separated from the molten mass, but that the gases in the molten globe and those in the atmosphere above took on a state of equilibrium relative to one another, the special terms of which are as yet unknown, but which were of such an order that a large part of the future atmosphere and hydrosphere was retained within the body of the earth. When, later, the external atmosphere was consumed by reaction on the surface rocks, the previous equilibrium was destroyed, and any residue of liquid material, charged under the previous condition, would, when freed from confinement, discharge an additional part of its gases. That portion of the mass which solidified under the earlier conditions of equilibrium may also be supposed to have retained much gaseous material, which was freed later under suitable conditions. Under this conception, the primitive atmosphere was much less extensive than that postulated by the standard form of the hypothesis, and much more gaseous material was held in reserve in the earth-body to actuate future vulcanism and to feed the atmosphere and hydrosphere.

With this basis, the modified view supposes that the formation of the crust was followed by a period of exceptional volcanic activity, and that this volcanic stage was so prolonged and so effective that the primitive crust was deeply buried under volcanic extrusions, and has since been rarely, if at all, exposed, and that the sedimentary series was derived chiefly from the volcanic series. Some of the extruded material is supposed to have constituted lava-flows and some of it massive embossments, while much of it consisted of the fragmental products of the explosive gases. As the series was built up, it became subject to intrusions forming dikes, sills, and batholiths. When the surface temperature had fallen below the boiling-point of water, aqueous action gave rise to sedimentary deposits which mingled, as minor elements, with the dominant volcanic constituents.

These features fit fairly well the characteristics of the earliest known rocks, as now interpreted. If this supplemental volcanic action be made extensive enough, the difficulty arising from the apparent absence of the rocks of a primitive crust is avoided.

The hypothesis thus modified is not altogether successful in meeting the atmospheric difficulties mentioned above (p. 86), for the primitive atmosphere, supplemented by the accessions of this great vo canic period, should have given a vast gaseous envel a history not altogether unlike that of the precedin less excessive in its terms.

The modified hypothesis furnishes a better ground view for elucidating the volcanic activity of later periods ing the loss of the atmosphere due to chemical combi surface rocks; but it is not clear that it is adequate. tion is offered as a possible emendation of the more of the gaseo-molten hypothesis touching two radica the latter seems to fail to meet the requirements of ac edge.

Stages under the Modified Hypothesis.

The stages of evolution under this view may be follows:

I. **The astral eon.**—The separation of the materi from the parent nebula and its aggregation into a r spheroid.

II. **The molten eon.**—The condensation of the rocl gaseous spheroid into a molten spheroid which was s hot vaporous atmosphere; but the molten spheroid never occluded within itself, some large part of the water of th sphere, as well as much of the carbon dioxide represen ent carbonates and carbonaceous deposits.

III. **The lithic eon.**—The solidification of the m beginning most probably at the center, on account c possibly continuing thence to the surface, but perhap at the surface, at a later stage, and solidifying down solidifying portions at length meeting, or partially rise to essential solidity of the whole. In this resp may be accommodated to the various phases of opini ject. The first mode of solidification is not altogeth the modified hypothesis, for the solidification rising fr not improbably force out the larger portion of the while the surface was yet liquid The view that the over while yet there was at least a deep molten layer the general conception, and 's the main basis for the l late.

IV. **The primitive volcanic eon.**—Prodigious volcanic action, closely following the solidification of the crust, during which the forcing out of lavas from below by the progressive crystallization of the remaining magma, or by plutonic stresses, was the leading event, the result being great beds of lava and tuffs on the surface, and later great intrusions of other lavas into and through these. The surface flows were formed largely of the more fluent lavas, and hence were generally of the basic or neutral class, and the pyroclastics were predominantly of the same type, while the intrusions were more largely, though not wholly, of the stiff acidic type. Later, under metamorphic action, the basic lavas became schists in part, and the acidic gneisses, neither class, however, excluding the other. Contemporaneously with this volcanic action, but quite subordinate to it, atmospheric and hydrospheric action is postulated, resulting in sedimentary deposits interlaid with the volcanic, but in greatly inferior quantity. The presence of life is implied by carbonaceous elements in the sedimentaries. This period corresponds to the Archeozoic eon, as limited by those geologists who separate the Archeozoic from the Proterozoic (Algonkian) system.

V. **The sedimentary eon.**—The remaining time, reaching to the present, is characterized by the dominance of atmospheric and hydrospheric action over volcanic, and is recorded by the ordinary clastics, sandstones, mudstones, etc., derived from well-decomposed rocks, and by limestone. It begins with the Proterozoic sedimentaries and extends to the present time, embracing the Paleozoic, Mesozoic, and Cenozoic systems.

Under this scheme, the accessible record is made to begin with some stage of the volcanic eon, but probably not the earliest.

III. STAGES OF GROWTH UNDER THE ACCRETION (PLANETESIMAL) HYPOTHESIS.

It is theoretically possible that the earth may have grown up by accessions in ways other than those sketched under the planetesimal hypothesis, as set forth in this work, and so it is necessary to recognize that accretionary evolution is not necessarily identical with planetesimal evolution, but the latter is taken as a type form and furnishes the basis for the following sketch of evolutionary stages.

I. The Nuclear Stage.

Under the planetesimal hypothesis, the earth is
started as a nebular knot, acting as a nucleus, an
gradually to its present mass by accessions. It doe
important, geologically, to consider the special sta
nucleus if it be granted, for the reasons previously
that it constituted only a small fraction of the gro
mass were quite small, there is reason to assume tha
of material of high molecular weight, since light
probably escape by virtue of their high velocities, ex
coherent with, or occluded in, heavier material. The n
to have been originally an assemblage of planetesimals
by their mutual gravity, and to have passed grad
nucleus in connection with the capture of outside p
the planetesimals were solid aggregates in the main,
elastic, their collisions mutually destroyed their o
a certain proportion of cases, and led to their collect
In other cases the orbital motions were increased, but
which were thus temporarily driven away were subj
capture.

II. A Possible Atmosphereless Sta

As the solid nucleus thus formed may not have bee
to control a gaseous envelope in its earlier stages,
phereless stage is to be recognized. Just how ma
body must be to hold permanently an appreciable
accurately computable at present, because of the
of some of the factors involved.[1] A fairly safe con

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[1] The following papers bear upon this subject: G. Johnstone
of the Absence of Hydrogen from the Earth's Atmosphere, a
from the Moon, Roy. Dublin Soc., 1892. G. Johnstone Ston
upon Plants and Satellites, Trans. Roy. Dublin Soc., 2 series,
p. 305. T. C. Chamberlin, A Group of Hypotheses bearing on C
of Geol., Vol. V, 1897, p. 653. G. Johnstone Stoney, On the P
the Earth's Atmosphere, and its Relation to the Kinetic Theo
Jour., Vol. VIII, Dec. 1898, p. 316. S. R. Cook, On the Escape of
Atmospheres according to the Kinetic Theory, Astrophys. Jour
p. 36. G. Johnstone Stoney, On the Escape of Gases from P
According to the Kinetic Theory, No. I, Astrophys. Jour., V

haps be drawn from known celestial bodies. The moon (1/81 of earth's mass) has no detectable atmosphere, nor has any smaller body, whether satellite or asteroid, so far as known. Mars (1/9.34 of earth's mass) has an appreciable but apparently quite limited atmosphere. The limit between atmosphereless and atmosphere-bearing bodies probably lies between the two, i.e., roundly, between 1/80 and 1/10 of the earth's mass.

The mass of Mercury, unfortunately, is not known with satisfactory accuracy, because it has no satellite and offers no other ready means of determination. Values all the way from 1/26 to 1/9 of the earth's mass have been assigned. Mercury gives no distinct signs of atmospheric refraction, and its reflection of light (albedo) is very low, even lower than that of the moon, and, like that of the moon, is relatively much stronger for surfaces normal to the line of incidence and of vision than for those oblique to it, which is characteristic of a rough surface. All this implies the absence of an atmosphere and hydrosphere of sufficient value to give effective reflection of themselves, or to develop a good reflecting body by smoothing down the surface and filling up the pores. On the other hand, certain lines of the planet's spectrum have been thought to imply the presence of water-vapor, but this is not conclusive. The probabilities seem to be that Mercury has no atmosphere that is effective as a weathering or degradational agent, which is the point of geologic interest. This brings the limit of appreciable atmosphere much nearer Mars than the moon, and justifies the provisional conclusion that if the young earth had no more than 1/20 of its present mass it probably possessed no atmosphere of appreciable geological efficiency, but that, when it had gained 1/10 of its present mass (radius probably about 2100 miles) an appreciable though relatively slight atmosphere surrounded it.

III. THE INITIAL ATMOSPHERIC STAGE.

The origin of the atmosphere.—The origin of the atmosphere under the gaseo-molten line of evolution has become familiar. Its origin under the accretion hypothesis is so different as to present more points of contrast than of similarity. When the growing earth reached a

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251; No. II, *Ibid.*, June 1900, p. 325. G. Johnstone Stoney, Note on Inquiries as to the Escape of Gases from Atmospheres, *Ibid.*, Vol. XII, October 1900, p. 201.

The gases chiefly occluded in meteorites and in rocks (Vol. I, pp. 619–620) are hydrogen, carbon dioxi oxide, in leading amounts, and marsh-gas and nitrogen tities. It is assumed that the gases of the aggregate and hence those of the interior of the early earth w order of abundance. There is experimental ground fo at the right temperatures and pressures, hydrogen wo from ferric oxide (which, from the analogy of igneous orites, may be presumed to have abounded in the ear therewith form water. The gases extruded from the therefore, have been largely water-vapor and the carb minor quantities of hydrocarbons and nitrogen. To added such chlorine, sulphur, and other temporary gase ingredients of the rock-material might contribute t action; but these chemically vigorous constituents soon disappear by union with the rock-material. It carbon monoxide would pass into carbon dioxide, as accumulate in the atmosphere, although abundantly marsh-gas also disappears in some way.

Summary of available material.—The material of tion available for the atmosphere, therefore, embrace vapor, carbon dioxide, and nitrogen. Oxygen is nov some abundance by volcanoes, but it is not known v comes from the interior, or has merely been carried surface. The reduction of ferric oxide under certain reverse of the process by which water is assumed to ha might possibly give free oxygen.

The material of external derivation might proba the atmospheric constituents, but in proportions unkn

The actual proportions of the atmospheric gases de earth's gravity.—In determining the actual proporti stituents of the early atmosphere, the abundance of probably less decisive than the power of the earth to ho gases. As the gravity gradually increased by the eart an incompetent minimum, its power to control the cules with the lowest velocities was acquired before it the lighter ones of higher velocities. According to th molecular velocities vary inversely as the square roo

highest velocities by the molecules of the atmosphere i
where the opportunities for escape were greatest. The
planetesimals may have been several miles per second
In a certain proportion of cases, the planetesimals v
molecules in such a way that the rebound of the latte
a large proportion of the planetesimal velocity with th
velocity, and would therefore increase their liability
the control of the young earth. Now in the impact
of watery vapor with the planetesimals, particularly
had acquired a white-hot temperature, the heat was su
ciate the oxygen and hydrogen in considerable propor
dissociated elements would take on the velocities app
respective weights, and would act individually until
mean velocity of hydrogen is more than four times
and it may be assumed that it would be at least fou
to escape from the control of the earth. Such excessi
leave a surplus of oxygen, even after the hydrogen th
had reunited with oxygen, as it would in time. As
impact was, by hypothesis, a very pronounced phenom
growing stages of the earth, it is assumed that a no
free oxygen might be accumulated by this dissociati
process, and that this, with that from other source
for the support of the earliest plant life, which, thoug
on carbon dioxide, required oxygen.

(2) As soon as plants were introduced, they may be
decomposed carbon dioxide, retaining the carbon an
oxygen as at present. While a portion of this oxyg
united with the vegetable matter on its decompositi
composing process was probably never complete, and
oxygen resulted. The oxygen of all the later periods is
derived from the decomposition of carbon dioxide
For the primitive atmosphere there is theoretical
enough oxygen to support the primitive plant life
supply itself, after which it would produce a surplus.

In the preceding discussion, the feeding of the at
extrusion of the internal gases has been assumed.
now to consider how extrusive action might be ini
maintained.

(1) **Heat from infall.**—The total amount of hea
the infall of the planetesimals would undoubtedly be
cient to melt the whole mass, if the heat were all g
same instant; but if it were generated in successive
over a long period, and generated at the surface wh
ated away, no large amount might be retained, and hi
such as required for vulcanism, might not be assignabl
In the present state of knowledge, the hypothesis
sonably be given such a form as to make this source
able, by assuming that in the early stages of accretion,
planetesimals were still relatively numerous, the co
them and the nucleus were so frequent as to make th
is possible that mathematical inquiries, contemplat
carried out, will show that this was probable, and that
tion so slow as to give a cool exterior would only com
planetesimals of the feeding zone had been thinned
that can be shown, the hypothesis must face the a
bility that the collisions did not succeed one anoth
to greatly heat the growing earth-body by impact.

(2) **Heat from quasi-gaseous condensation of t**
unknown amount of heat may have been inherited f
knot that constituted the original earth-nucleus. T
posed to have consisted of an assemblage of small
from the heavy molecules of the nebular material;
chiefly the metallic and the rock substances. This
because these substances would condense to the liqui
at high temperatures, and further because, having low
ties and relatively high gravity, they could assemble
ciated by mutual attraction, while molecules of low
velocities could not. These assemblages were prob
revolutionary, but perhaps rather irregularly so,
way between a well-organized planetesimal system
neous gaseous or collision-rebound system, and co
the qualities of each. The ingathering of planetesi
out probably tended to increase the irregularity, a
assemblage to become more and more gas-like in
The matter being rock-substance or metallic, and
plastic, and the collisional velocities generally low,

The hypothetical mode of vulcanism. — With th ceptions now developed, the method of volcanic actio the accretion hypothesis, may be readily apprehende part which it began to play in earth-history may b chief portion of internal heat being assigned to compr perature must have been highest at the center and mu toward the surface. By referring to pages 563-569, tribution of pressures, densities, and temperatures for will be found. These elements must have had the sa tribution, in a general way, for any of the immatu earth, but there should have been some differences i value because sources (1) and (2) named above woul negligible elements as the earth grew to its maturity.

Melting due to outward flow of heat.—Pressure it incompetent to melt rock-substances that shrink in the high temperatures generated by pressure in the de constantly moving outward into horizons of lower the melting-points were lower. As the computed ter center of the adult earth is about 20,000° C.,[1] there w no lack of heat, in the later stages at least. The esse lem lies in its redistribution and in its selective act distribution and its outward flow have been set for referred to in Vol. I.

Selective fusion.—The material of the interior wa hypothesis, an intimate mixture of planetesimals of with such gaseous material as they carried in, or en process of growth. This material, therefore, presuma the most fusible to the most infusible of rock-material the form of aggregated planetesimals. As some of i of the kind that shrinks much in solidifying, and some shrinks little in solidifying, and some, possibly, of th not shrink at all in solidifying, it is probable that some c near or even to the melting-point by pressure, wh intimately intermixed with these, were far from thei At any rate, the outward flow of heat, in such a mix some parts to fusibility much before the melting-poin

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[1] A more elaborate discussion of internal temperatures due Mr. Lunn, will soon be published under the auspices of the Carne

reached. Local spots of fusion must thus arise. To this fusion,
ntrapped and occluded gases may be presumed to have contrib-
and to have joined themselves to the fused masses, and to have
in giving them fluidity.

e dynamics of ascension.—As the rise of temperature continued,
and more of the mixed material reached the fusing-point, while
material so nearly approached it as to become plastic and per-
eadjustive movements. In this way, fused parts were permitted
in one another and to move in the direction of least resistance.
static pressure from the earth-body itself was always greatest
r and least above, but was nearly constant for any given short
d. The stresses arising from the differential tide-producing
ctions of the sun and moon were also greatest below and least
e, but were *periodic*, stress and relief following one another in
daily succession, giving a kind of kneading process (Vol. I, pp. 578,
and 629–632). These interior stress-differences are thought to have
ed the fused vesicles outward, causing them to unite and form
ds or stringlets, which insinuated themselves through the more
ctory portions that remained solid, and at length developed into
ues of some volume. As these liquid threads or tongues rose
igher horizons of lower pressures, and hence of lower melting-
ts, they carried with them a certain surplus of heat above that
ired to maintain their liquidity in the new horizon, and this sur-
was available for melting or fluxing their way. They were at
same time, however, subject to loss of heat by contact with sur-
ding rock of lower temperature. They were thus, probably, at
same time taking up fusible material met in their path, and deposit-
old material as it became less adapted to remain fluid under the
conditions, either because it had reached the point of its satura-
in the mixed rock-solution that had been developed, or had cooled
ts point of congelation. The liquid thread was thus presumably
ng on and giving up material continually as it worked its way
ard, the process always being selective, and involving the reten-
of the more soluble or more fusible portions, and the rejection
he less soluble or more refractory portions. Since the included
s may be safely reckoned with the former class, there was a selec-
accumulation of these, and the ascending liquid became densely
rged with them. To this ascensive process, those substances whose

weight overbalanced the differential pressure, such as n possibly the heaviest silicates, may be regarded as forr

Arrested ascensions and attendant heating. — Tl require that these threads should all succeed in reach indeed, it does not require that any should, in the initi compression had developed a great excess of heat in tl The molten threads should simply rise until their exce working capital, was exhausted, when they would ret state and constitute tongue-like intrusions. In doing t contribute heat to the tracts which they invaded. Thi conduction, was a mode of conveying the intenser h pressed central regions to the higher horizons, where t perature and the fusion-points were both lower. Th earlier threads to reach the surface would thus be a tory to the greater success of later ones. The cond tration would probably be favorable up to the horizon perature ceased to be higher than the surface meltin this the retention of the solid state was wholly due temperatures being above the surface melting-poi threads reached the higher zone, in which the tempera ciably below the surface fusing-point, the conditio adverse, and further ascent was dependent on a suff heat, brought from below, to maintain the liquid s adverse tract was being traversed. It was probably on a fluxing power adequate to enable it to fuse its w solid zone of continuous rock that lies below the fractu it reached the latter, hydrostatic pressure and the inh force of its gaseous content would probably control its in the main.

Now, having in mind that, at the early stage unde the earth was growing, that its internal self-compressio apace with its growth, that the heat was rising with t that the temperature was highest at the center and the surface, that the heat was therefore always flowing face, and that it was also carried outward by the liq succeeding steps may be followed easily.

Invasion of the fragmental zone and surface explosi part of the young earth was made up of the recently nals and their fragments, and no doubt had a much broken, open texure. If there was, as yet, no atmosphere or hydrosphere, as in the ase of the moon, there was no effective means for the washing of fine ragments into the interstices of the coarse, or, what is more imporant, for the solution of the material at the surface and the cementaion of that below into a solid mass, as is the present habit on the earth; n other words, there was no effective healing process to unite the broken ragments. The porous clastic zone nust, therefore, have extended lownward to a depth at which ravity was able to force the fragnents into continuity by its crushng effects. In a small body this one would be deep.

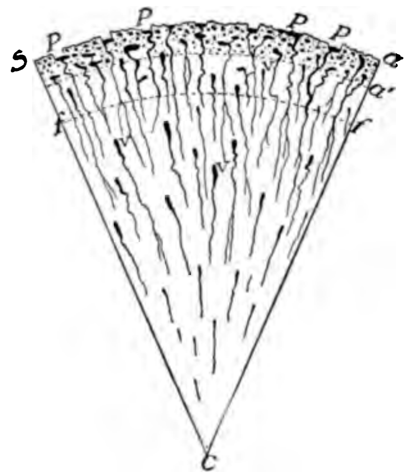

FIG. 32.—Ideal section of a portion of the early earth, illustrating its assigned modes of vulcanism. *C*, center; *S*, surface; *a–a′*, fragmental zone; *a′–f*, zone of continuous rock below surface melting temperature; *ff–c*, interior portion whose temperatures rise from the surface melting-point at *f–f* to a maximum at *C*; *V*, *V*, threads or tongues of molten rock rising from the interior to various levels, many of these lodging within the fragmental zone as tongues, batholiths, etc.; *PPP*, explosion pits formed by volcanic gases derived from tongues of lava below.

When the rising lava-tongues eached this outer fragmental zone, luxing was no longer required, as hey could force their way by insinuation and by mechanical displacement. It appears almost certain hat, in the upper part of such a ragmental zone, the interstices would nake up a sufficient part of the volume of the aggregate mass to reduce ts average specific gravity to a figure below that of the penetrating ava, even though the latter might be made up of lighter material inherently, and was also hot and liquid. The earliest tongues of molten material are supposed, therefore, to have generally lodged within the fragmental zone, taking various plutonic forms, as dikes, sills, laccoliths, and batholiths, and to have there given off their gases, which, more or less concentrated and condensed, doubtless not infrequently forced an exit to the surface by blowing away the overlying fragmental material (Fig. 32). The slight coherence of this material, the low gravity of the young earth, and the absence or scantiness of a resisting atmosphere should combine to give to the pit-forming dinary magnitude, such, perhaps, as the moon exhibits (598).

Volcanic action not necessarily antecedent to the atm not necessary to the hypothesis to suppose that volca an essential preliminary to the acquisition of an atmos it came into function before the earth acquired an a the initial atmosphere may have been supplied from e The apparent vigor and the wide prevalence of volcani moon, if its pitted surface means vulcanism, as well as the found in meteorites, whose origin is referred preferably phereless bodies, favors the view that the internal g forth abundantly before the earth grew to a mass su them. If this were true, an ample source of atmosphe ready and waiting when the earth first acquired suffic clothe itself with a gaseous envelope.

V. The Initial Hydrospheric Stage.

The origin of the ocean.—When the increasing wat growing atmosphere reached the point of saturation, it form and became a contribution to the hydrosphere. densation had occurred within the fragmental zone external atmosphere reached saturation. The hydr fore, probably had its birth underground, and so long a zone retained its highly porous condition, it was what i a veritable sphere or spheroidal layer. As the wat rose to the surface, and doubtless first appeared in t pits resulting from the previous volcanic action, and in resulting from other deforming agencies. Its surface therefore, pictured as a growth from innumerable la with unknown promiscuousness over the face of the yo more and more enlarged and confluent bodies, until developed into the vast, irregular oceans of to-day. of fundamental geologic importance, for it involves t ocean basins and of the continental platforms, and at once the grand topographic features of the globe, t of deformation, and the controlling physical factors a selective action of this kind began. The surface areas that remained exposed lost more of its basic th constituents, while the submerged material lost less, and something by the redeposition of the matter borne in As the planetesimals were being gathered in on land a those that fell on the land suffered some atmospheri those that fell into the water were mainly protected fr differential action affected each successive layer of gr accumulation of surface waters began, *the specific gra areas came to be less than that of the submerged areas.*

Permanent versus temporary effects. — It is not specific gravity that resulted from the change of physica in disintegration that is to be considered here, but ra be termed the inherent or permanent specific gravity, gravity that would be retained after any metamorp material might probably suffer in the future had ta likewise it is not the temporary chemical combination diately from the weathering, but the potential futur that are significant. For example, any rock likely to residual sands, earths, and clays by any probable m even by remelting, would have a lower specific gravity t average rock, or than any rock likely to be developed f and alkaline earths removed by the leaching proces with the original rock. The leaching of the land mat fore, a permanent effect on its specific gravity, an effec by any probable change resulting from its burial under tions. The earth segments built up by accretion on hence lighter than the segments built up under the difference increased as the segments grew in thickness

The progressive depression of water-covered areas.— the greater weight of the water-covered segments that beneath them, as they became more and more weighte material, was greater than the compression beneath the and hence the water-covered areas were depressed than the land-areas. The waters drawn in upon the ments augmented the depressing effects due to differ gravity.

It is not necessary to suppose that there was, a

into the water-basins, and other influences modified
the deepening and spreading of the water-basins is l
been a markedly dominant process during the earth's
growth ceased and modern processes became dominan
balanced relation of sea and land is thought to have
close approximation to constancy.

Configuration of basins accidental or systematic?–
the original depression of the areas occupied by the w
to have been slight, and, we prefer to think, accident
There may have been systematic causes that determi
depression of certain broad tracts and the relative ele
such as some systematic difference in the infall, or
change, or some inherent tendency to shrinking in c
ways, as for example that held by advocates of a tet
but it is not clear that the actual distribution of depres
tions points to such systematic agencies. The elevate
tracts of the moon seem to have a distribution quite
the earth, and those of Mars, if the lighter and dark
rectly interpreted as elevated and depressed tracts, ar
from those of either earth or moon. Each seems to
itself, if such irregular distributions can be styled a l
hypothesis requires nothing more than the inevitable s
of growth, of volcanic activity, of compression, and th
Starting with only such slight differences as were s
preponderance in large tracts in favor of the water or
selective and self-propagating nature of the process
the rest.

Smallness of the differentiating action.—If it be as
earth's growing hydrosphere appeared at the surface
had attained the mass of Mars, whose radius is about
subsequent growth would form a shell about 1900
is not altogether certain that Mars bears water-bodie
but the areas of greenish shade, environed by a surface
the polar white-caps ("snow-caps") that come and go
and the apparent occasional presence of clouds, not t
evidence of aqueous absorption-lines in the spectrum r
good observers, but unconfirmed by others, lend some

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[1] Emerson, Presidential Address. Geol. Soc. Am., Vol. II, pp

tive that the initial forms of life had been introduced
else that an evolution quite out of harmony with that
took place in the unknown interval antecedent to the
the life was introduced is also quite unknown. The
it might have been brought to the earth from som
body by a fragment, in the form of a meteorite, is
from supposed geological, biological, and philosophi
a merely temporary refuge in the face of prodigious
for it only throws back the problem of life-genesis wi
There is nothing in known meteorites, save perha
of hydrocarbons equally assignable to inorganic sou
that they came from worlds with atmospheres and hyd
to maintain such life as the problem presents. On th
are the best of grounds for believing that meteorites c
in which the essential conditions of life were wanting
absence of free oxygen and water, there is an absence
assignable to weathering and to those rock-changes t
the presence of an atmosphere and hydrosphere. T
large portion of all known rocks in the outer part of
as are characterized by quartz, orthoclase, the acid
micas, the amphiboles, etc. (Vol. I, p. 467), as well as
rocks. The absence of these in the meteorites is pecu
because of their abundance in the earth. The hypoth
importation of life encounters a special difficulty un
hypothesis, in that *the planets were all forming at the sa*
the other hypotheses, the outer planets may have for
the inner ones, and an earlier evolution of life may h
in one of the older planets, whence a transference to th
conceivable. Under the accretion hypothesis even this
refuge, and transfer from some other stellar system is
recourse.

Available time.—The accretion hypothesis affords
lapse of time between the stage when conditions cong
first possible, and the stage when the first fairly le
made in the Cambrian period. To this unmeasured
pre-record evolution of life, whatever be its method,
with every presumption that the time was ample, and
sion for an evasion of the profound problem of life-ge

up by the inner planets, may have screened off some ap the sun's heat and light; but the ratio of nebular mat probably too small to render this loss critical. So lor itself remained luminous, the nebular light compensat less degree for the solar light cut off, but perhaps n The nebulous surroundings of the growing earth must reduced the loss of heat by radiation into space, an some compensation.

Autogenic heat and light. — There was, howev source of heat and light of critical importance, nam from the infall of the planetesimals. If this infall we ficient to heat the surface of the earth above 100° C., li types would have been prohibited. The present sta does not permit any very confident opinion as to wh was reached or not. Leaving this question open, it is if, at the stage when first an atmosphere and hydrosph the infall of planetesimals was so rapid as to heat the hibitive temperature, the rate of infall must almos declined as the number of planetesimals in the ear was diminished; so that, long before the supply wa growth ceased, the rate must inevitably have fallen be ive limit. If, therefore, the earth were too hot f fifth grown, its temperature might have become sui one fourth, one third, one half, or three fourths grow this permissive stage was reached would be slow, required for its completion would still be long.

Transition to complete solar dependence.—In the danger seems to be all on the side of too great h sun's heat were much less than now, the heat of p would probably make up the deficiency and more. continue to be a source of home supply so long as t tinued, declining as the supply of planetesimals diminution of the supply cleared the space between sun, and gradually brought the latter into full functi therefore, be a gradual passage from the partial d home supply of heat and light, to complete depend supply. There is little ground for apprehension t planetesimals would be seriously dangerous to the e for, in the first place, the atmosphere must have been then, as now, an effective cushion checking the speed of the planetesimals and partially dissipating them, and, in the second place, the early organisms were probably all aquatic and were further protected by their water-covering.

Changes in the atmosphere inaugurated by the introduction of life.—The introduction of organic activity brought into play those chemical processes that have been sketched in general terms in Chapter XI of Volume I. The changes in the composition of the atmosphere are especially important. It has been shown (p. 97) that the primitive atmosphere probably contained a preponderance of carbon dioxide, and, a little later, carried all the water-vapor that it could hold under the prevailing temperatures, while the amount of nitrogen was not improbably low, and that of oxygen uncertain. If only there were oxygen enough to serve the functions of plant life at the outset, the existing large content of oxygen could probably all have arisen from subsequent plant action. It is merely necessary, therefore, to assume (1) that the carbon dioxide was not too abundant to prohibit the development of the early plants, (2) that the oxygen was sufficient for their vital processes, and (3) that the nitrogen was much less abundant than now, to give a good working basis for the evolution of the present very different atmosphere. Assuming that green (photosynthetic) plants were first introduced, and that, until some time later, there were no animals or predaceous plants that decomposed the carbon compounds produced by the green plants, the effect of plant life on the atmosphere would be to reduce its carbon dioxide and increase its free oxygen. If there were no check or offset to this process, a relatively short time would suffice for the conversion of an atmosphere of dominant carbon dioxide to one of dominant oxygen. If the present vegetation can remove the present content of carbon dioxide in one hundred years (see pp. 639–644, 645, Vol. I), an amount of carbon dioxide as great as the whole atmosphere of to-day might be changed to oxygen in about 300,000 years by an equally active vegetation. The early plant action may have been much less efficient than that of to-day, and the requisite period might be correspondingly lengthened, but it might still b geologically short. Besides, the early atmosphere, by hypothesis, w much less abundant than the present one, and probably much n active in the carbonation of rocks.

It is assumed that life requiring a high content of c appear until after the composition of the atmosphere had changed in this way. After oxygen-consuming, carbon-organisms came into existence, the reciprocal action of of life tended to maintain an equilibrium, though no between the oxygen and the carbon dioxide in the air. time, the carbon dioxide was continually uniting with stance of the outer part of the earth, as it does now, and removed from the atmosphere. The same is true of tl probably then, as now, oxidation was less active and carbonation. And so the combined result of plant life a action was to bring down the content of carbon dioxide t place. The nitrogen, being relatively inert, graduall and has now become much the most abundant consti

The great factors now all at work.

So soon as plants and animals had come into action factors potential in the earth's physical evolution were the psychologic element remained to become a potent in the history. But though all were in function, their were by no means equal, and the future stages were successive dominance of one or another leading agent these was the dominance of vulcanism.

VII. THE CLIMAX OF VOLCANIC ACTION.

By hypothesis, volcanic action only began some beginning of the earth's growth, for it was delayed (of sufficient compression in the central parts to give the and (2) by the time required for this central heat to mo of less pressure, where it would suffice to liquefy the m stituents. But once begun, it gradually increased in relative importance until it reached its climax. This c much later than the climax of growth, for it was dep growth to give the increased compression from which ar heat on which the vulcanism depended. And so, owing of delay just cited, the maximum of volcanic action mu much behind the accession of the material which rem it. It is, therefore, inferred that vulcanism continued to increase in activity long after growth had entered on its decline, and that there was an important period in which the dominant activity was volcanic.

The ratio of the volcanic products to the accessions and to the derivatives.—It is conceived that in the late stages of the earth's growth the amount of material poured out on the surface in molten form, or introduced into the outer parts of the earth from below, was very much greater than the accessions from without. Still later these declining accessions were so overwhelmed by the igneous extrusions that they became indistinguishable contributions. In this stage, too, it is held that the modifications wrought by the atmosphere, the hydrosphere, and organic life were also quite subordinate to the volcanic contributions. Disintegration is assumed to have gone little farther, usually, than to partially reduce rocks of the granitoid type to arkoses, and those of the basic type to wackes. Rather rarely, it is believed, was much pure quartzose sand, aluminous clay, or similar well-decomposed residuary material accumulated; rarely, also, much carbonaceous shale. Arkoses and wackes, when metamorphosed later, took on such a similitude to igneous rocks as to be more or less unidentifiable.

The Archean complex.—The formations of this period of volcanic dominance, with very subordinate clastic accompaniment, are regarded as constituting the Archean complex, though perhaps only the later portions of the great volcanic series are represented by the *known* Archean. Here, for the first time, we reach formations exposed to view, and observational geology begins to replace the hypothetical. As interpreted in the light of the recent studies in both the Old World and the New, the lowest accessible formations that can be given a place in the systematic series were originally surface lava-flows, attended by volcanic clastics in abundance, and by sedimentary clastics and chemical and organic deposits in quite subordinate quantity. Into these were intruded contemporaneously, and also at later stages of the same great era, enormous embossments of granite and other rocks. This intricate combination of surface flows, clastics, and intrusions, distorted, sheared, and metamorphosed, makes up the vast Archean complex.

Diastrophism accompanying the volcanic climax. — For obvious reasons the great climacteric era of vulcanism was attended by deformations of exceptional intensity. The transfer of so much materia from below to the surface required a readjustment, while the intrusio

of the enormous granitic batholiths of the Archean wer
a source of deformation. Great changes in the distri
perature were involved in the outward flow of the mol
carried heat outward from the deeper zones, and exp
in the zones through which the rising lava passed. T
fore, loss of both material and heat in the lower zon
material and heat near the surface, with the obvio
principles set forth in Vol. I, pp. 564–568, relative to the
of heat by conduction and its double effects were al
harmony with this intensive combination of agencie
rocks, as we shall see in the next chapter, are extrao
and crumpled, and at the same time phenomenally trave
sheets, tongues, and embossments of plutonic rock
probably had its climax with the climax of vulcanism,
by hypothesis, about the time of the opening chapter
history of the earth.

It is at this stage, and with the great agencies
one another, that we reach the lowest observable fo
earth's body, in following the accretion hypothesis.
student to judge for himself whether the postulated
felicitously or otherwise into the actual state of t
oldest known rocks reveal. The value of a hypothesi
stration of its truthfulness is not yet possible, lies in its

VIII. The Great Stage of Atmospheric and H
Dominance.

To complete the survey of stages, it is necessary t
through the remaining ages and note the great fact
of the earth having ceased, and volcanic action having
the surface of the land was no longer subject to conti
was exposed, age after age, to the action of the atm
attendant work of streams and ground-waters. The
by these agents was deposited in the basins. Throug
therefore, the dominant phase of geologic activity be
atmospheric or gradational, as nearly as it can be exp
in a single word. Vulcanism and diastrophism conti
important accessories, but not the controlling fact

embraces the Proterozoic, Paleozoic, Mesozoic, and Cenozoic eras, the chief portion of known geologic time.

Synoptical View of the Earth's History.

If we take a sweeping view of the stages of the earth's history from first to last, they fall into two great groups, with a transition period between them: *the stages of growth and the stages of maturity*, with an intervening transitional stage. In tabular form, and numbered in chronologic order, these stages appear as follows:

III. THE GRADATIONAL EON (Relative maturity)	11. The Cenozoic era		C. The better known eras.
	10. The Mesozoic era		
	9. The Paleozoic era		
	8. The Proterozoic era		
II. THE EXTRUSIVE EON (Transitional)	7. The Archeozoic era		B. The partially known era.
	(Under planetesimal hypothesis)	(Under gaseous hypothesis)	
I. THE FORMATIVE EON (Birth and adolescence)	6. The initial life stage	The initial life stage	A. The hypothetical eras.
	5. The initial hydrospheric stage	The congelation stage	
	4. The initial atmospheric stage		
	3. The initial volcanic stage	The molten stage	
	2. The atmosphereless stage		
	1. The nuclear or nebular stage.	The gaseous or nebular stage	

SUPPLEMENTARY CONSIDERATIONS.

I. THE DIFFERENTIATION OF THE ROCKS DURING THE STAGES OF GROWTH.

The general nature of the process by which the surface rocks of the continental areas were, by hypothesis, rendered more acidic and less heavy, has been set forth. To show more fully the bearing of the hypothesis on the general characteristics of the crystalline rocks, and on some of the outstanding problems presented by them, there is need to enter somewhat further into details, though the subject cannot be fully elaborated here.

The average original material.—If meteoritic material represents, in a general way, the average of the heavier and more refractory material of the siderial system, as seems probable from the fact that it comes from all quarters of th heavens and seems to represent almost as many different parent bodies as the are distinct meteoritic falls, it may be regarded as the type of what was the aver earth-material in its *atmosphereless* state, if it had such state. If there be ad to this a certain unknown proportion of the lighter and less refractory mat

that could not be retained in the gaseous state by a small body
taken to represent the material of the full-grown earth. Th
probably not remove the total average earth-material very fa
of the meteoritic matter, and so, with some qualification, met
be taken as a rough, but somewhat too basic and metallic, sta
earth-material.[1] It is easy, however, to gain a false impress
nature of meteoritic material, for the stony meteorites are le
than the iron ones, and hence a less proportion are recogni
the stony meteorites usually disintegrate rapidly and soon dis
if not found promptly, are not found at all. If, therefore, the
averaged include simply those that are found, the result will
in metallic material. The true average should include only
On this basis, Farrington concludes that the true average is
tially by stony material of the basic silicate type, with only a s
of metallic material, and that the average specific gravity is ab

Volcanic differentiation.—It will be recalled that from an
material is supposed to have been poured out on the surfac
buried by the infalling planetesimals. At the same time,
slightly weathered on the land-areas, and such of the materi
was carried into the water-areas. Later, when the surface ha
built up by accessions, this same material was exposed to a s
canic experience, with further selective fusion and further surf
Still later, the process may have been repeated, perhaps ag
the first volcanic surfaces, may possibly have been as much as
below the present surface, and the number of possible repetiti
round is large. A wide differentiation from the original state
sible. As the last series of extrusions came after the cessat
accessions from without, *practically nothing but the various vari
tiated product would appear at the surface.* That these should dif
original average rock is not strange; but why they should dif
ways in which the surface rocks differ from the supposed av
to be worked out, and the solution of this problem will, in so
of the validity of the hypothesis. It is to be borne in mind
not a mere selection based on the melting-points of the min
surface rocks, but is rather the outcome of a complex process
and precipitation in which the modifying conditions of tem
ratio of admixture, stress-differences, and specific gravities, pl

Differentiation in suboceanic versus continental segments.–
to assume that the lavas which arose from the more basic segn
the deep-sea basins would be more basic than those that ar
acidic land segments, and this seems to be supported by the gr

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[1] For composition of meteorites, with references to the literat
Jour. of Geol., Vol. IX, 1901, pp. 393 and 522.

[2] Jour. of Geol., Vol. V, 1897, p. 130.

when its meaning shall be demonstrated. The climax of found in the iron-bearing basalts of Greenland, in which little are scattered promiscuously through a stony base in meteorit

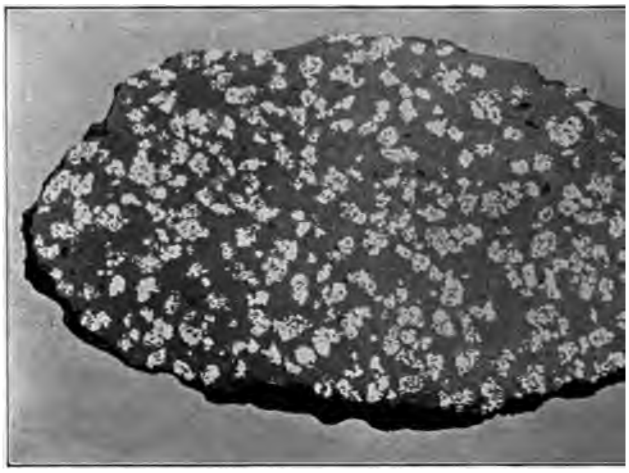

FIG. 32*b*.—A pronounced example of igneous rock composed of ferent specific gravities that show no signs of separation by The light portion is native iron, which has more than twice the basalt, the dark portion, through which it is promiscuo Kaersut, Nugsuaks peninsula, Greenland. (After Phale Coll., Vol. I, p. 199.)

in Fig. 32*b*. In this case the specific gravity of the meta that of the embracing stony matter.

II. DEFORMATIONS UNDER THE PLANETESIMAL H

Relative to deformation two great eras are to be recogn and that following the cessation of growth. During the chief cause of change of bodily form is assigned to the a This enlarged the geoid, and at the same time tended to co tional gravitative pressure. Heat arose from this compressi dissipated, tended to prevent further compression. There nism between the opposing processes of growth and shrinkag the former dominated.

When growth ceased to be appreciable, this type of diast dominant, but its effects were more or less perpetuated. I the chief agencies of deformation are thought to have bee material, with some extrusion, a re-distribution of heat in th of heat from the surface. Incidentally there was some gene in the previous era, but this is not presumed to have equalled

This twofold division of earth-history may be regarded to three great stages of diastrophism, a first, in which accessions to the exterior, resulting in compression and heat, were dominant; a second, in which the transfer of molten material from the interior to the exterior, involving the transfer of heat, became dominant, this being the great volcanic stage that followed the main stage of growth; and a third, embracing the hydro-atmospheric eon, including most of the known geological history down to the present, in which diastrophism seems to have been dependent mainly on the re-distribution and loss of heat and the internal re-aggregation of material, and subordinately on the shifting of sediments. Obviously, these several stages were not separated by hard and fast lines, but rather graded into one another insensibly, and constituted merely successive phases of dominance.

THE MODES OF DEFORMATION.

Reasons have already been given for believing that the water-covered areas would acquire higher specific gravity than the land areas, and would, therefore, take precedence in sinking, both in time and amount, and that thus the great basins and the continental elevations would arise. If deformations were limited to these greatest features of the earth's relief, the explanation might rest here; but their surfaces are still further diversified by plateaus, anti-plateaus, and folded mountains, as well as by the minor phenomena of faulted blocks, warped surfaces, etc. Some of these, as the folded mountains, especially when attended by overthrust faults, imply a compressive lateral movement (Vol. I, pp. 500–510); others, as the sunken blocks attended by normal faulting and gaping fissures, imply crustal tension (Vol. I, pp. 510–525). The problem therefore embraces not only the massive shrinkage supposed to have given rise to the abysmal basins and continental platforms, but such accessory actions as were competent to give rise to the plateaus, folded mountains, and lesser protuberances of a compressive type, and to inequalities of a relaxative type. (For preliminary discussion see Vol. I, pp. 542–589.)

The earth may be conceived to be formed of great sectors whose bases are the several ocean bottoms and continental platforms respectively, each constituting a cone, pyramid, or wedge, with its base at the surface and its apex at the center of the earth. Assuming these factors, for the moment, to be units of action, certain conceptions can be tested.

1. If the sub-oceanic and continental sectors all shrank in equable proportions in every part and simultaneously, the sectors would settle down within their own spaces and no unequal crowding would follow, and hence no crumpling. This is certainly not the actual case.

2. If the outer parts of all the sectors shrank proportionately more than the inner parts, each sector could not only have settled down within its own space, but could have permitted some tensional fissuring and faulting without involving lateral thrust or folding. This is certainly not the actual case.

3. If the sub-oceanic sectors simply contracted radially more than the continental sectors, to the extent of about 3 miles, the continental-oceanic reliefs

would have been attained, but the crumpling of the contin
be left unexplained.

4. If the sub-oceanic sectors sank first, for the reasons pr
by virtue of their superior gravity, wedged aside and squeeze
sectors between them, the continental surfaces would doubt
crumpled, and great reliefs and surface distortions be produ
But would the *proportions* of lateral thrust and continental el
the facts? While it is necessary to recognize that no estimate
of lateral thrust involved in the mountain folding that has
is more than roughly approximate, we have previously taken
figure representing the apparent order of magnitude of the
due to folding since the pre-Cambrian times, on an entire cir
p. 551). If, without change of volume, the continental se
proportionately throughout their mass by the sinking ocea
their surface breadths were reduced 100 miles, in the aggrega
ference, they would be protruded several times as high as th
is obvious that this is not the whole of the actual case, thou
step toward it.

5. We have heretofore recognized the possibility that ov
distribution of heat in a self-compressing earth, the tempe
rising in the outer 800 miles or so of the earth, while it is sink
this may bring to bear special crowding in the outer parts (V
It may be, also, that crystallization has limits determined by
and that only a certain outer zone is crystalline while the c
miscible state, or in some unknown state of superior density.
the outward distribution of heat and slightly increasing g
might lead to the encroachment of this central mass upon t
by transformation from the crystalline to the miscible or
This would result in a crowding of the crystalline zone on it
adjustment to the shrinking central mass, in a manner analo
crowding of the superficial crust on the shrinking subcrust.
other and unrecognized ways, the outer parts of the sub-oce
posed to thrust the outer parts of the continental sectors relati
central parts crowd one another, surface distortion, greater t
case in proportion to the continental elevation, would re
approach to the true case would be attained, but the propor
wide of the true ones. But the *kind* of effect that would be pr
normally, seems to suggest the source of a needed factor. If
miles thick, were thrust against another segment of like thickn
the latter 1 mile, with only negligible change of volume, the s
segment must be raised a mile over an area 800 miles in widt
Some change of volume by compression would be inevitable,
conception here sought it may be neglected. Such crow
ments seems to be of a kind suited to form plateaus, for the
ably be a swell or uplift whose breadth was more or less comp

f the distorted segment. The principles controlling the distribution of s is thought to require this. Thinner segments should give plateaus of less th, and their heights should be determined by the extent of lateral thrust. ch cases, the crumpling at the surface would be small relative to the whole tion. Some tension might even be developed on the top of the swell. eaus are commonly affected by much tensional faulting, but this may be due ly to the secondary action presently to be noted. They are also often affected he more superficial distortions of the crust yet to be considered.

6. Under the hypothesis of a molten earth, it is agreed very generally that if olid crust formed over the interior while the latter was hot and expanded, and at if the interior cooled and shrank later, the crust must have been too large for contracted core and must have wrinkled to accommodate itself to it, involving rizontal thrust. If such a crust, whether formed in this or any other way, aving a thickness of 20 miles, were thrust laterally 40 miles—Lesley's estimate of he amount of lateral movement involved in the folding of the Appalachian ridges n central Pennsylvania[1]—and folded into a mountainous tract 60 miles wide, nd if the volume of the rock were preserved by upfolding, the average height of he upfold would be 13 miles, an amount which is quite out of accord with the acts. It is obvious on numerical inspection that no crustal thickness of this order of magnitude can give rise to the actual foldings with the actual elevation, if the approximate volume is preserved by upfolding simply. If preserved by infolding, which would probably be the normal mode in a floating crust, the result should probably be a synclinorium at the surface, with a very different expression from that which is actually presented. If the crust were mashed so as to give up-swelling in small part, and down-swelling in much larger part, a closer approximation to the real case might be made, but even then it is doubtful whether the configuration would be what it is.

With an earth solid throughout, whether from accretion or otherwise, no such disproportionate downward swelling is admissible. The thrust of a thick crust is competent to form a plateau, with some crumpling, but apparently not the requisite folding of the folded mountains with their limited elevations.

7. All hypotheses that postulate a solid globe, and perhaps all others, must apparently also postulate a shearing zone at a depth such that the amount of the lateral thrust correlated with the thickness of the thrust shell, shall correspond to the height of the folded tract, when suitable allowances are made for the compression and extension of the rocks, perhaps for some downward displacement, and for other incidental results, all of which are probably of small value. It is of prime importance to determine what this thickness is.

The thickness of the folded shell.—The thickness of the folded shell appears to be deducible from the extent of the thrust, as shown by the folds, combined with the average height and breadth of the folded tract. For example, if a thrust of 40 miles was involved in the folding of the Appalachian ridges in central Pennsylvania, as Lesley estimates, and if the highest fold was arched about 5 miles,[2]

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[1] 2d Geol. Surv., Penn. Summary, Final Rept., 1903, p. 206.

[2] 2d Geol. Surv., Penn., Pt. X, p. xxi, 1885.

probably a rather high estimate, the average elevation of the
degradation may be taken at 2.5 or 3 miles above the previous
for compression, extension, and possible downward thrust
immaterial for present general purposes. The present width o
about 60 miles; its original width was therefore, by estimate,
shell that has been crumpled from a width of 100 miles to a wi
in so doing has raised its surface 2.5 miles, on the average, m
nally 3.75 miles thick, neglecting possible changes of density,
average surface 3 miles, it must have been 4.5 miles thick,
A similar method may be applied to other mountain ranges for
estimates of crustal shortening and of the heights of the folde
and the results are of a similar order of magnitude. It appea
phenomena of the folded tracts themselves indicate that only a
immediately involved in their formation.

The conclusion that a shell of a very few miles only was inv
lings of the folded mountains is so important as to invite mo
of the shortening of the crust, of the dimensions of the folds,
elevations of the folded tracts than have thus far been made,
more critical measurements and perhaps new methods.
proved data, a shell of perhaps 3 to 5 miles thickness may be t
tive. This is found to be in reasonable harmony with o
For example, a normal fold cannot well be less than twice t
folded strata until these have been closely recurved upon the
by transverse pressure, and this only occurs when close appress
selection of the available cross-sections of the Appalachian fol
in folios of the U. S. Geological Survey, measured liberally
lowest dips of the flanks, gives an average width of about 8
more closely so as to include the more distinctly folded por
miles. The halves of these fall within the range above gi
of other mountain ranges, so far as available, are of similar im

The shear-zone.—If we seek reasons for the limited thic
shell, and for a shearing-zone so near the surface, they may
the relations of the weight to the rigidity of the crust, or the
crushing-strength and shearing-strength. Available data as
rocks are very inadequate, and only tentative applications
experimental tests have usually related to the crushing-stre
shearing-strength. They are also usually made on selected r
are hence probably higher than the average rock in its na
They are clearly higher than the native strength of rocks nea
much weakened by fissuring, leaching, and other superficial cha
depths, however, these weaknesses disappear, and the rocks
continuous and sound. At greater depths, compression pro
strength, while increased heat tends to reduce it, but for the
this discussion neither of these factors probably becomes vital
average crushing-strength of the granites that have been ex

out 25,000 pounds per square inch; that of the limestones about 16,000 ds; and that of the sandstones about 6000 pounds; while that of shale, h has scarcely been tested at all, because unfit for building purposes, is reciably less than that of sandstone. At the depths where the shearing-zone ears to lie, crystalline rocks undoubtedly exist in higher proportions than r the surface, and so the average ultimate strength undoubtedly rises toward higher figure given, as the depth increases. It is to be noted, however, that ong the crystalline rocks some have less strength than the granites tested.

Now, at a depth of a mile the vertical pressure arising from the weight of the erlying rock is about 6000 pounds per square inch, while the resistance of the ck to crushing is probably as great or somewhat greater than indicated above. At this depth, therefore, on the average, the weight of the rock will be insufficient o deform the crust by crushing, and thus adapt it to the shrinkage of the interior. The crust must meet the tendency of the interior to shrink away from it by a tendency to develop a parting, and thus bring into play the principle of the dome in its support, and thereby develop a tendency to lateral thrust. Now as previously shown (Vol. I, p. 581), the strength of even the best rock is utterly incapable of resisting the thrusts of the flat dome of the earth's crust when fully brought into play. At 3 miles depth the weighting has increased to about 18,000 pounds per square inch, at 4 miles to about 24,000 pounds, and at 5 miles to about 30,000 pounds. Within this range the weighting must approach, and perhaps pass the crushing-strength of the average rock involved. Down to the point where the weighting equals the crushing-strength, the tendency to arching with accompanying lateral thrust, must take precedence over the tendency to crush. At points appreciably deeper, where the weight is greater than the crushing-strength, deformation by flowage is the normal result. The distinction here is analogous to that between the zone of fracture and the zone of flow, as developed by Van Hise and Hoskins,[1] but is not strictly identical with it, for here lateral thrust and shearing-strength are essential factors. The zone of shear reaches higher than the zone at which fracture becomes impossible under radial stress alone. The zone of shear is perhaps identical with the lower part of the theoretical zone of fracture and the upper part of the zone of flow.

Folding in tracts of least resistance.—Now since the shrinkage of the interior is a slow and essentially simultaneous process, the shearing-stress probably develops an essentially simultaneous thrust over large areas, and as the shell offers much resistance to local folding, a conjoint shear for large areas—in distinction from numerous local independent shears—is developed, involving a common movement of large portions of the shell toward some tract of least resistance, where relief is found for the whole stress in a concentrated folding. Tracts of low resistance are obviously found (1) at or near the borders of the continents, where the crust is already flexed in its descent from the continental platforms to the ocean bottoms; (2) in tracts back from the borders of the continents where special flexures have been developed by deep sedimentation and attendant down-bowing; and

[1] 16th Ann. Rept. U. S. Geol. Surv., I, 1894–95, pp. 589–603, 845–859.

(3) in tracts that have been weakened by previous folding o initiate folding, the lateral thrust of the shell must not only the shearing resistance at its base, but also to the resistanc weak tract to folding.

It must be confessed that the extent to which a common l to have taken place is greater than might have been anticipat considerations. Shears for short distances only and moderat points might have been expected, rather than shears of m vast tracts by a common movement which concentrated their in a single folded tract. It is perhaps not strange that the ocean basin should have thrust laterally from its center to it was already flexed and weak, but the great concentration of cases, and the fewness of the folded tracts in any given fold indicate that a conjoint movement of even greater extent took

Periodicity.—While the ulterior causes of folding may be continuous action, and hence folding liable to take place at times in different parts of the earth, and more or less continu of geologic history seems to indicate that there were long peri stresses, followed by shorter periods in which the stresses r by a rather general deformation of the several kinds indicated cannot be said to be held universally, however.

Supposed combined action.—From the foregoing considerat conception of a typical deformation of the major order is c Presuming, in accordance with the sketch of the stages of grow basins and continental platforms have been determined previ that the transfer of material and heat in the body of the ear from the surface, and, probably most important of all, the m ment of matter in the interest of greater density, gradually cumulated stress enough to overcome the effective rigidity of the earth, and to cause a general shrinkage. For reasons p this is supposed to have been inaugurated in the sectors beneat which are assumed to have shrunk radially, and to have cro jacent sub-continental sectors to the extent of causing a slig in their elevations.

It is also to be assumed that, more or less locally or reg parts of the oceanic and continental sectors, and perhaps s specially upon one another for considerable depths and in va that these special deep-seated thrusts gave rise to the mas constitute plateaus. In neither of these cases, however, was great, nor did it contribute much to superficial crumpling. It i interior shrinkage involved the descent, relative to the center, sectors as well as the sub-oceanic, but to a slightly less degree. sectors have been spoken of as being crowded up, or caused to elevation, in accordance with the common usage of terms in t subject. These terms relate to *the average level of the surface,* plane of reference, not to absolute distance from the center of the earth. Rightly understood, these are proper terms, dynamically, since it is *the relation of part to part* that produces the distortional effect. There is a very closely related conception, which needs, however, to be distinguished from this, that of the shrinkage (settling) of the general crust away from certain portions, leaving the latter protuberant. Such areas, left above their surroundings by circumjacent depression, have been called *horsts*.[1] While the existence of horsts is not ques-

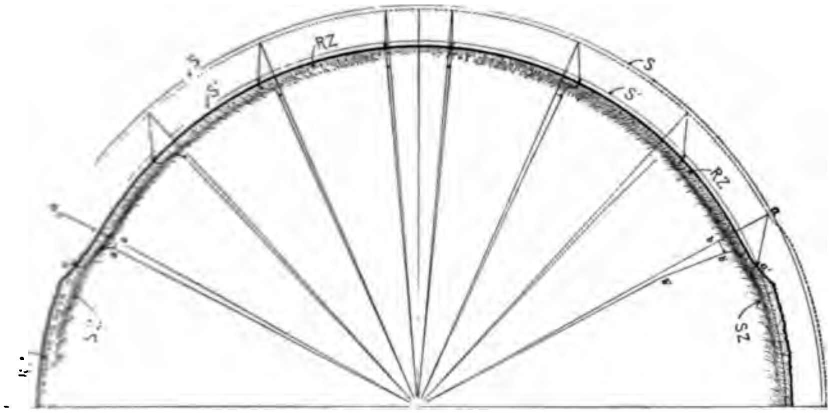

Fig. 32c.—Diagram illustrating the supposed elements of a general deformative movement. *SS* represents the outline of the sphere at the ocean level before deformation. The dotted line represents the corresponding surface of the lithosphere, the ocean basin occupying the center and the continents the flanks. *S'S'* represents the outline of the sphere at the ocean level after deformation, the heavy line representing the outer surface of the deformed lithosphere, and the space between *SS* and *S'S'* representing (much exaggerated relatively) the vertical shrinkage which is the great feature of the movement but is only made apparent through its deforming effects. That part of the outer shell which is beneath the ocean is supposed to descend without much compression, while the necessary folding is concentrated on the borders of the continent. The central portion beneath the ocean is represented as descending directly toward the center. The portions on each side preserve their length by thrusting laterally and hence descend along paths represented by the arrow-headed lines of which those at the border of the ocean *a*, *a'*, are the most oblique and represent the greatest thrust. On the borders of the continent the crust is folded to the extent of this lateral thrust. This of course only holds true when the thrust is limited to a single oceanic basin. The lateral thrust is chiefly felt in the outer shell or rigid zone, *RZ*, which embraces the heavy line and the dotted zone below. Beneath this lies the shear zone, *SZ*, whose foliated structure is represented as not unlike that of the "drag" belt of a fault plane. The igneous sheets, batholiths, etc., which are supposed to especially affect this zone, are not represented. The great sector beneath the ocean is represented as having crowded slightly upon the sectors beneath the continents on either hand, this crowding being represented by the short arrows *b*, *b'*. By comparing *bb'* with *aa'* the reason for the shear zone will be made apparent. On the right-hand side the outer part of the sub-oceanic sector is represented as crowding upon the continental sector an exceptional amount, as represented by the deflection of the line *b'b''*. This gives rise to the plateau at the right. The proportions of most of the significant parts are necessarily exaggerated relatively.

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[1] Suess, Das Antlitz der Erde, p. 167.

tioned, as will appear later, they are conceived to belong to a
different from that of the great plateaus here under discussio
of the latter, while the whole outer portion of the earth is su
descending, the plateaus included, *the parts mutually crowd*
resulting in the relative displacement of some of them by p
squeezing, and mass distortion. The dynamics here were p
parts were concerned, not negative, as in the case of true hor

The superficial shell, not having undergone the molecular
assigned to the interior, and hence not having shrunk pro
supposed to have accommodated itself to the shrunken in
previously described, and as commonly held under all h
illustrates graphically the supposed movements acting conjoi

The zone of accommodation. — Between the folded she
where flowage-deformation prevails, there is presumed to
modation by which the one is adjusted to the other. This zo
is supposed to be affected partly by shear and partly by fl
the nature of the formations of which it is composed at an
nature of the stresses which there affect it.[1] It is presum
shear along a few selected planes above, through shear along
middle, to continuous shear, or flowage, below, and thus to co
zone from the shell to the main body.

The shear-zone a zone of foliation.—The more distributive
in this zone would obviously give rise to foliation and schist
therefore, the shear-zone becomes a zone of foliation, practi
globe next beneath the rigid shell. Under the planetesimal
is supposed to have been gradually lifted as the growth of
and hence to have undefined depth. In those portions of
were protruded above the sea at an early date, and that w
material for the sedimentary rocks, it is conceived that thi
tensively exposed, and constitutes, in part at least, the foliat
as Archean; indeed the Archean areas are conceived to
portions of the shearing zone that have been brought to the su
of the shell that once overlay them.

The relations of the shear-zone to igneous intrusions. — Fr
be seen that the shearing-planes are flexed as a result of lat
that, typically, their section is a double curve, the middle p
not be greatly removed from the horizontal. It is conceived
reaching this zone in its passage outward from the interior,
to follow the shearing-planes already developed, these bei
resistance. The rising molten rock must often have been so
the course of its passage, and hence residual portions arrested

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[1] Technically, flowage takes place by shear, but it is the shear
other adjoining part, while in the more common usage here
confined to selected planes.

the shearing-zone may well be supposed to have given rise to that alternation of sheets of igneous rock and foliated rock which constitutes a common and typical phenomenon of the Archean terranes. It may well be supposed further, that the more viscous igneous rocks, by gradually stiffening, might often lodge in the more nearly horizontal stretches of the shearing zone, in large, flattened, disk-like lenses, and constitute batholiths. The enormous areas occupied by the Archean batholiths seem to find in this an explanation that does not involve the serious displacements of adjacent rock usually assigned to them.

Secondary or tensional movements.—In the foregoing primary deformations the movements are essentially compressive in effect. Incidentally, some tension is involved in particular portions, as on the tops of folds, and perhaps on the great arches of the plateau-swells, and elsewhere. These primary processes therefore offer no adequate explanation of the prevalence of tension in the outer part of the continents. As these tensional phenomena are widely prevalent, they imply a general cause. They are here referred to secondary action, following upon the primary deformation. In the sinking of the great sectors and in their mutual crowding, especially in the formation of plateaus, it is held that portions of the continent were relatively elevated above the plane of isostatic equilibrium, and, as the mass of the interior, though solid, is not absolutely rigid, there is ground for the presumption that the excess of gravity in the protuberant portions was gradually relieved by their slow sinking; in other words, a secular movement in the direction of isostasy would follow the periods of deformation. This view is especially applicable to the great plateaus. A direct movement downward, which would be the primary phase of an isostatic movement, would, however, tend to develop thrust, but because of the protuberance a lateral creep is postulated. Such a creep is postulated regardless of isostasy. The continents now rise about 3 miles above the average ocean bottom, and much more than that in certain portions. Since the volume of the ocean has probably not greatly changed during known geological time, and since the continents appear to have risen to and above the surface, about as now, in the earliest known geological ages, it is assumed that similar differences of relief have prevailed at the various known deformative periods. We have seen that the gravitative pressure at 3 miles depth is nearly or quite as great as the shearing-resistance at that depth. If a shearing-zone at depths of 3 to 5 miles had already been developed during the primary deformation, this would facilitate a reversed movement along the same shear-planes. It is therefore conceived that the continental platforms, by pressing upon their bases to the extent of 16,000 to 30,000 pounds to the square inch, would, though opposed by perhaps 5000 pounds per square inch pressure from the oceans, gradually creep laterally under their own gravity, in a slow glacier-like way. This supposed lateral creep should be attended by crevassing, fissuring, and normal faulting; in other words, *by the prevalent tensional phenomena which the continents present.* It should be much more marked in the plateau regions than elsewhere, because of their superior elevation, and it is there that normal faulting is most pronounced.

Horsts, rift-valleys, etc.—In a tensional movement of this kind, affected by various inequalities of bottom, of the shear-zone, and of r certain blocks of the shell may well be supposed to settle awa leaving them protuberant as horsts. Certain other blocks m lower than the adjacent ones, to fill the vacancy made by the neighboring blocks. Tiltings, rift-valleys, and other phen tensional areas would be natural accompaniments.

Relations to sedimentation.—Lateral creep from continents should gradually lower the continents, particularly at their bo a landward creep of the sea, giving rise to tracts of shallow wa seas) well adapted to the shallow-water sedimentation whic the continental areas during the course of known geological furthermore, give rise to slight changes of elevation, by reason ment over inequalities of base. Gentle warpings, undulatio should occur, as in glaciers, and for like reasons. Moveme because of their extreme gentleness, would be admirably a those common phases of stratification in which a nearly co hanging depth of water is maintained for long periods. Th also constitute an element in base-leveling.

On the borders of the continents, such supposed creep several peculiar results that will be discussed under the periods, since they seem to have specially manifested themsel

3. According to the planetesimal theory, the core of th is made up of planetesimal matter, perhaps correspon in composition to meteorites. After aggregation, th matter was probably recrystallized under the influen and pressure which the aggregation involved, the resul essentially igneous in its nature. Outside the central c therefore be (1) a thick zone made up largely of plane

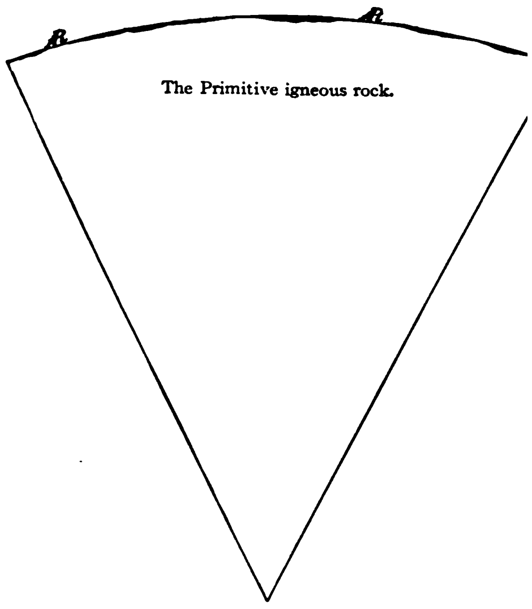

Fig. 33.—A diagrammatic sector of the earth illustrating its stru the Laplacian hypothesis. The great body of the earth is mad igneous rock. Sedimentary rocks, together with some extrusi a thin coating, represented in the diagram by black, outside interior. The original igneous rock is represented as appearin some places (Æ). This, according to one view, might repr rock.

but partly of igneous rocks erupted from below, and partl rocks. The planetesimal matter is assumed to pred lower and major part of this zone; igneous rock, eruptiv is assumed to have a somewhat irregular distribution the sedimentary rock increases in importance above, th throughout a very subordinate constituent. This zo growth of the earth from the initiation of volcanic a processes to the close of the period of notable growth by accretion. The central core and this thick zone about it represent the Formative eon (p. 119). (2) The next zone, probably a relatively thin one, is assumed to be made up dominantly of extrusive igneous rocks, with which would be associated subordinate amounts of sedimentary matter and matter gathered in from space. This zone represents the Extrusive eon (p. 119). (3) Outside it lies the superficial zone in which sedimentary rocks predominate, though associated with not a little rock of igneous origin. The first two zones outside the core are assumed to be universal, while the outermost zone, being composed primarily of material washed down from the land and deposited in the sea, fails to encircle the glob

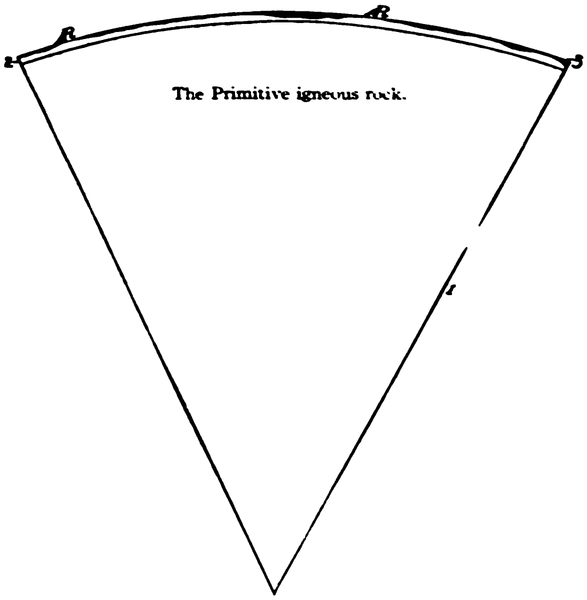

Fig. 34.—Diagrammatic sector of the earth illustrating its composition on the modified form of the Laplacian hypothesis. As in the preceding figure, the great body of the earth is made up of the original igneous rock. Outside this original igneous mass, there is, according to this hypothesis, a zone of extrusive material, with perhaps some sedimentary rock intermingled. This is represented by zone 2 in the diagram. The material of this zone is represented as coming to the surface at two points (*Æ*). Outside this zone, there is a third zone made up primarily of sedimentary, but subordinately, of extrusive rocks. According to one interpretation, the material of the second zone might constitute the Archean rock.

The oldest accessible formation.—With these ideal sections in mi it is pertinent to inquire what might be the nature of the oldest formations accessible, on the various hypotheses which represent. The deepest excavations yet made in the little more than a mile in depth, and while, by reasor and erosion, rocks which once lay at greater depths bel have been exposed, the maximum thickness of rocks op tion is but a few miles. Knowledge of rock formations ı based on observation, is therefore limited to some such

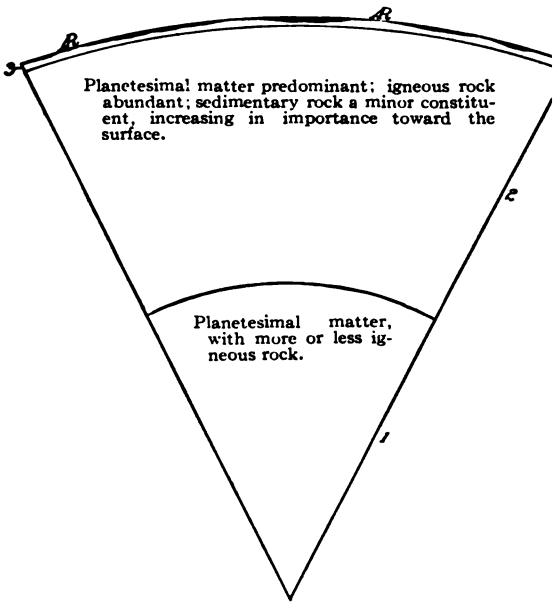
R
R
3
Planetesimal matter predominant; igneous rock abundant; sedimentary rock a minor constituent, increasing in importance toward the surface.
2
Planetesimal matter, with more or less igneous rock.
1

Fig. 35.—Diagram representing the structure of the earth according mal hypothesis. The material of zones 1 and 2 is indicated in th 3 of this figure corresponds to zone 2 of Fig. 34, and zone 4 of sponds to zone 3 of Fig. 34.

1. On the simpler form of the gaseo-molten hypoth hope to reach the original crust; for, considering the d rocks are exposed, it is not rational to suppose that principal source whence sedimentary rocks were derived, covered so deeply by the derivative material as to t 2. According to the modified form of the gaseo-molte oldest accessible rock might not be lower than the deeper zone of mingled extrusive and sedimentary rocks interm the original crust below and the dominantly sedimentary

On the planetesimal hypothesis, the oldest rocks to which we might pe to gain access would be those referred to the Extrusive eon (p. 19), during which more or less sedimentary rock was mingled with e volcanic. On this hypothesis, as on the preceding, no sharp line f demarkation would be expected between dominantly sedimentary ocks above, and dominantly non-sedimentary rocks below.

The rock-formations now most widely exposed at the surface are edimentary, and were therefore formed during the time of atmospheric nd hydrospheric dominance, that is, during the great Gradational eon (p. 119). In not a few places, however, formations of dominantly extrusive-igneous or meta-igneous origin are found, either beneath the prevailing sedimentary rocks, or projecting up through them in uch relations as to show their greater age. In many cases these inferior rocks were thoroughly metamorphosed, and in essentially their present condition, before the deposition of the overlying beds, for masses of metamorphic rock derived from them are included in the non-metamorphic series above. These igneous and meta-igneous formations which antedate the oldest known series of rocks made up chiefly of sediments, are the oldest rock-formations known, and the era during which they were formed is therefore the first era of which there is definite record in the accessible formations of the earth.

These rocks consist of a very complex series of formations, embracing lava outflows, volcanic tuffs, igneous intrusions of various types and exceptional extent, together with some sedimentary deposits, ll usually metamorphosed and notably deformed. Distinct fossils ave not been found in these rocks, but the occasional presence of 1) carbonaceous shales very similar to younger shales which derived heir carbon from organic sources, (2) iron-ore beds similar to those hich owe their origin to plant action, and (3) occasional limestones nd cherts which, as a class, are usually the products of organic ction, are thought to imply the existence of life, and to warrant lacing the era when these rocks were formed in the "zoic" group. his view is supported by the theoretical probability that life extended ack through a vast period unrecorded by fossils, since the earliest ssils yet found imply a very prolonged antecedent evolution. The a during which, or during the later part of which, this oldest system accessible rock-formation was made, is the *Archeozoic* era.

Under the planetesimal hypothesis, the oldest known rocks may be confidently referred to the Archeozoic era, for, a hypothesis, rocks of organic origin and rocks containi ucts were not only mingled with all series that are acc an indefinitely deep series below, since life is supposed t long before the earth acquired its growth. The o known may also be Archeozoic under the modified ph hypothesis which has been presented (p. 88); but u form of the hypothesis of a molten earth, the original placed in the Archeozoic system, for its formation ante ance of life. It must therefore be assigned to an e "lithic" era (see p. 83). Since recent investigations re doubtful whether any accessible rocks can be referred original crust, there is little ground for referring any an azoic era antedating the Archeozoic.

To avoid all difficulties arising from doubt as t extension of organic rocks, the non-committal term system, Archean complex) is commonly applied to here referred to the Archeozoic era. This term is pr to the oldest group of accessible rocks, whatever t whether contemporaneous with life or antedating it

Delimitations.—The lower limit of the Archean s to be inaccessible. Its *upper limit* has been fixed at by different authors. The term Archean (very old introduced to displace the older terms *Azoic* (without (dawn-life), whose etymological meanings made inadmissible and sometimes of uncertain applic the term was made to include all rocks below the a bearing (Cambrian and later) systems; but progressive that there are three or more great systems of sedi sedimentary rocks (with interbedded igneous sheets with one another, between the Cambrian sedimentarie great complex of igneous and metamorphic rocks bel thought by leading geologists especially engaged in of these formations, that the pre-Cambrian system sedimentary rocks should be separated from the do or meta-igneous complex below.[1] Following their

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[1] Irving, Seventh Ann. Rept., U. S. Geol. Surv., pp. 448–454, an U. S. Geol. Surv., pp. 491–493.

Cambrian systems of rock, composed chiefly of sediments, are here separated from the Archean, and designated *Algonkian* or *Proterozoic.* The former term is commonly used by members of the U. S. Geological Survey, and by some others, though it is little employed outside the United States. It has the same terminal form as Cambrian, Silurian, etc., terms applied to groups of strata of a much lower order of importance, and hence the term Proterozoic, corresponding to the terms of higher rank, seems a better name for the great group of systems between the Archeozoic below and the Paleozoic above. Since these systems are very thick and separated from one another by great unconformities, they represent a vast lapse of time, probably quite comparable in importance to that of the Paleozoic, Mesozoic, or Cenozoic, or perhaps even to all combined.[1]

There are theoretical reasons of some weight for separating from the Archean complex all series of rocks that are made up, in large part, of quartzose sandstones, mudstones, and limestones, or their metamorphic equivalents. These rocks are made up of the products of *mature weathering,* and therefore imply that the surface from which their materials were derived was long exposed to chemical decomposition *without very favorable conditions for wash;* otherwise partially decomposed products would have been carried away and deposited before decomposition was complete, and the result would have been arkoses and wackes rather than quartzose sandstones and shales. A covering of vegetation is the chief agency that now prevents this premature wash, and secures mature decomposition. While it may not be wholly safe to conclude that a vegetal covering of the land was a necessary condition for the formation of the quartzose sands and the muds which enter largely into the systems referred to the Proterozoic, it seems best to entertain this presumption to the extent of separating these systems from the more ancient complex of rocks in which the products of such complete decomposition do not seem to prevail. The term Archean is therefore here restricted to those formations, composed chiefly of igneous and meta-igneous rocks, which antedate the oldest known dominantly sedimentary system. Since the Archean system of rocks, as thus defined, is primarily of extrusive-igneous or meta-igneous origin, the era during which they were formed is, under the planetesimal hypothesis, regarded as the time of transition from tb

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[1] Van Hise, Bull. 86, U. S. Geol. Surv., p. 491.

earlier *Formative eon* to the later *Gradational eon* (p. 1
to the modified form of the gaseo-molten hypothesis al
rocks may be referred to the Extrusive eon.

General Characteristics of the Archean.[1]

The Archeozoic era was characterized by great v
as shown by the nature of the formations, and by gre
and metamorphism, as shown by the deformations and a
the rocks had suffered prior to the Proterozoic era
rocks of no later era are so largely igneous, so notably
highly metamorphic. Because of these characteristics,
tion of these rocks is difficult, and such views of th
and correlation as are now entertained are to be held sub
tion as investigation proceeds.

Subdivision.—Recent investigations seem to inc
oldest parts of the known Archean consist of altere
of lavas, and pyroclastic rocks. This implies a p
surface on which the flows took place, and therefor
these are not the earliest rocks that were formed.

Associated with the metamorphosed surface lava-s
clastic formations there are occasional beds of meta
glomerate and shale, and beds of jasper and iron ore, all
contemporaneous water-action. Some metamorphosed
sandstones are probably also to be included in the
probable also that arkoses and wackes, produced by pa
and wash, are to be included. Such formations may h
dant, though not now recognized, for after they are

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[1] The Archean was formerly thought to be composed entirely of
igneous rocks; see Bull. 86, U. S. Geol. Surv., pp. 478–484, and
U. S. Geol. Surv., Pt. II, pp. 747–756. The character of the Arch
these publications needs some modification in the light of more
The sedimentary character of parts of the system is set forth in th
XLV, U. S. Geol. Surv., pp. 129, 172–212; 21st Ann. Rept., U. S. G
and 402–404; Mono. XXVIII, U. S. Geol. Surv., pp. 186–188; Am. G
1901, pp. 14–19; Jour. Geol., Vol. X, p. 71; Rept. of Bureau of
1902, pp. 155–162; Geol. Surv. of Canada, Vol. III, Pt. I, F, 18
Sci., Vol. 50 (1895), pp. 58–69. Trans. Roy. Soc. Canada, 1899
reference to Canadian localities, the rocks now classed as Ar
described under the name of Lower Huronian.

it is difficult to distinguish them from pyroclastic rocks and their metamorphic derivatives.

At a later stage there were great intrusions of molten rock into these surface formations, breaking them up and distorting and metamorphosing them in greater or less degree. It is not probable that the process of intrusion was distinctly separated from the process of overflow, but the intrusions, as we now find them, must have been preceded by the formation of the rocks into which they were intruded. To a phenomenal extent, the intrusions seem to have taken the form of massive batholiths, so that when the overlying rocks were cut away by erosion, as they have been since, the batholiths came to occupy large areas, and appear, on first study, to constitute a great formation by themselves. They were in fact so interpreted until recently, and seem to make up a large part of what has been called the *Laurentian* formation.

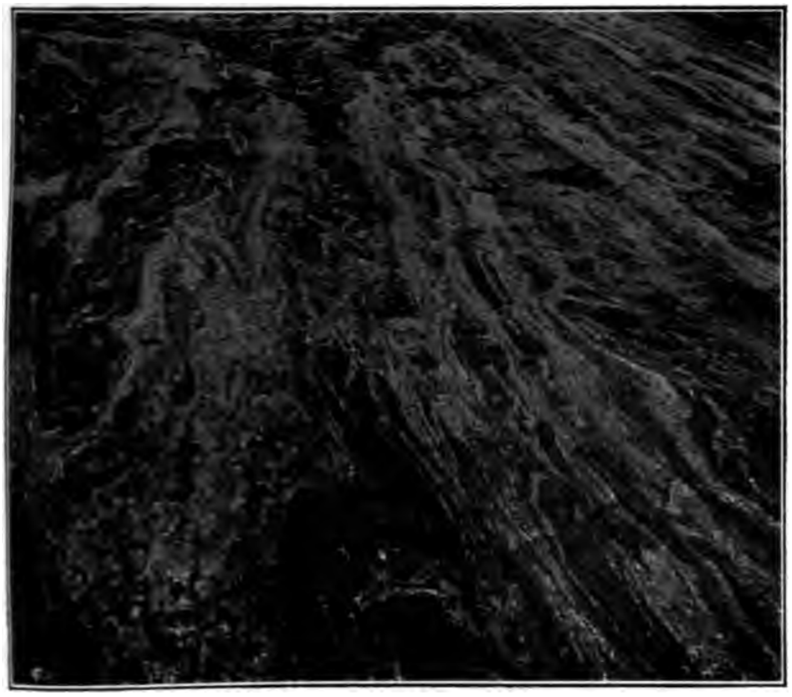

FIG. 36.—Figure showing the crumpled and contorted structure characteristic of much of the Archean rock. From a Canadian locality. (Ells.)

It is not improbable that the Archean is really n plicated than this rather simple statement implies. it consists of a much more extended succession of form indefinitely downward, a succession such as might during the processes of evolution sketched in the pı But at the present stage of investigation it is perhaı a general view to recognize two great classes of forma up the definable Archean, viz., (1) a great schist ser series, and (2) a great granitoid series or group of seri

(1) **The great schist series.**—The schists of this seri morphosed products of the lava flows, volcanic tuffs, a sedimentaries. The transformation involved both kat anamorphism; i.e., the lava-flows were mashed down ir structure (metamorphism) and the clastics, while al the schistose form, were built up molecularly into a c ture (anamorphism). In some portions, however, the condition of the lavas is retained. In composition tl massive igneous rocks vary greatly, but since the material is of the neutral and basic types, the commor rocks are hornblende schists, greenstone schists, mi The local formations of the Lake Superior region, th the Kitchi schists, the Quinnissec schists, and the schists are regarded as members of this group. How far these series are equivalent, and how far they represent succe it is not now possible to say.

(2) **The great granitoid series (Laurentian).**—Amon spicuous features of the regions of Archean rock, in thei condition, are the great masses of granite and gneiss appear as embossments protruding through the schists, rock, over great areas. Like the schists, they are less by later intrusions. Until recently, these grani were rather commonly regarded as the oldest known ing to this view they constituted a basal formation, an "primitive" or "fundamental." The granites in once quite generally regarded as portions of the origi supposed molten globe. The associated gneisses an rocks, however, were sometimes regarded as the highly products of very early sedimentaries, supposed to ha

from the original crust under the peculiar conditions of a very hot, acid atmosphere. The granites and gneisses came to be widely known as the Laurentian formation, on the belief that they constituted a distinctive basal series; but it is now known, in many instances at least, that they are intrusions into the schist series. They are therefore younger than the latter. The gneisses are now regarded, in the main, as metamorphic rocks derived from granites by metamorphic action which mashed the massive rock down into the foliated condition.

In the formation of both the surface flows and the intrusions, the ascending lavas must have occupied numerous fissures or conduits connected with the interior, and hence there came to be numerous dikes and other forms of intrusions, traversing such parts of the Archean formation as had already been formed. It is also to be borne in mind that all subsequent igneous action required passageways for the lavas through the Archean, and that they also gave rise to traversing dikes and intrusions of later date. These later intrusions, many of them called Laurentian by Canadian geologists, are of course not properly of Archean age, but they are not always separable, and their presence adds to the complexity of the Archean as a whole.

Similar formations not Archean. — To avoid misapprehension, it is to be observed that granitic intrusions are not confined to the schist series above described. There are granitic embossments associated with younger systems of rocks; but it appears from present knowledge that such intrusions are much more local and incidental than in the Archean system, where they are so dominant as to constitute a leading and distinctive feature. It is also to be observed that there are, in various regions, great series of gneisses and schists, with associated massive crystalline rocks, which are not Archean at all, but metamorphosed portions of later formations.

A special characteristic feature.—A not uncommon feature in the American Archean is a series of numerous thin sheets of igneous rock a few feet or a few yards apart, which penetrate the gneisses or schists in directions more or less parallel to their foliation, giving rise to a coarse interleaving of later igneous and earlier foliated rock. This is so common as to be regarded by Van Hise as characteristic of the Archean, since it is not known to prevail in any later formation. These interleaved dike-sheets are commonly truncated at their junction with the overlying Proterozoic formations, which shows that they we

formed not only before that series, but before the erosi
the Archean prior to the deposition of the base of the

The diastrophism of the Archeozoic era.—It is
intrusion of the great granitic masses was in itself
in the distortion which the schist series suffered, b
be assumed that the development of the schistose
bodies of massive igneous rock was effected simply
of lavas. Much less can the crushing down of ex
granite into gneiss be assigned to their intrusion in
The simplest and most satisfactory explanation of the
structure, of the interleaved igneous sheets and of the
to be that previously suggested (p. 130), which refers
chiefly to the shearing zone between the outer shell
interior. If this be not entertained, some help towa
is the conception that the extensive introduction of
in the earlier series of surface formations, resulting in
and distortion, would leave the whole in a conditi
develop extreme irregularity and intricacy of str
sufficient diastrophism was brought to bear upon t
these conditions, the included bosses of granitic rock w
well situated for the development of the concentric
which is a common feature of the Archean system.

In still another way (p. 117) igneous action prob
deformation of the rocks. The transfer of so mu
below, and its introduction into the outer parts of th
lateral pressure, not only by the intrusion and by
panying it, but also by causing the outer parts to se
the place of the material transferred from below.
lavas spread upon the surface tended to the same
result would be lateral thrust in the outer parts of t
thrust would be relieved by the bending and crum
(Fig. 37), and by shear. Under the circumstances, t
irregular and intimate. Superposed upon this were th
distortion which were operative with peculiar inten
stages of the earth's evolution, as previously indicate

Metamorphism.—That the rocks should have u
dinary metamorphism under the conditi
It has been demonstrated that w

have been crushed and sheared so as to develop a foliated or schistose structure.[1] It is in the rocks of this era primarily that metamorphism of this type is most commonly found. This is now regarded as having been a very extensive phenomenon, the larger part of existing gneisses, as well as a considerable portion of existing schists, having acquired their foliated structure by mashing and shearing. It is not to be overlooked, however, that some of the schists and perhaps some of the gneisses arose from clastic formations by anamorphic processes.

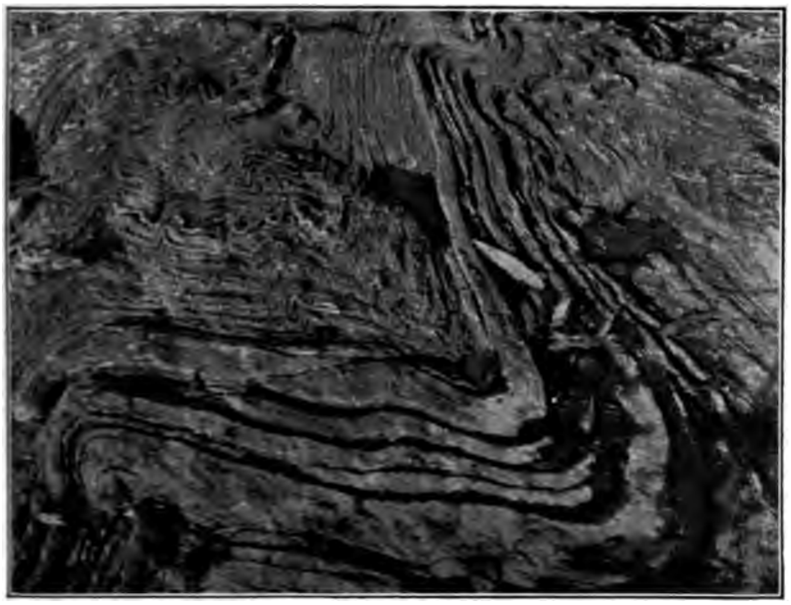

Fig. 37.—Figure showing the crumpled and contorted structure characteristic of much of the Archean rock. From a Canadian locality. (Ells.)

Distribution and Local Development.

General distribution.—The Archean is the one accessible rock system which is theoretically universal, in the sense that it underlies

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[1] E. Emmons, Report of the Midland Counties of N. C., 1856; Lieber, Second Ann. Rept. on the Progress of the Surv. of S. C., 1858; Irving, Geol. of Wis., Vol. I., pp. 340–61; Adams, F. D., Rept. of the Brit. Assoc. for the Adv. of Sci., 1886; Williams (G. H.) Bull. 62, U. S. Geol. Surv. and Proc. Am. Assoc. for the Adv. of Sci., 36th meeting, 1887; and Van Hise, Sixteenth Ann. Rept., U. S. Geol. Surv., Pt. I. and others.

the whole surface of the globe. No later system does t
the Archean comes to the surface all later formatio
and some of them are absent elsewhere. In speaking o
tion of a formation, it is generally understood, unless
cated, that its distribution *at the surface* is meant, and
its surface distribution, the mantle rock, glacial dri
overlie and conceal it are usually ignored, unless the
as to make the underlying formation indeterminab
surface distribution of the formation is given, therefo
be understood that the formation is literally at the surf
within the area specified, but that it is actually exposed
within that area, and that between the points of exp
uppermost formation beneath the mantle rock. In
Archean rocks are estimated to appear at the surface
fifth of the area of the land; but since much of Asia, Af
America, and the less accessible portions of other grand
only been reconnoitered geologically, this figure has on
a general estimate.

In North America,[1] by far the largest area of Ar
in Canada. It occupies nearly the whole of the Labr
and stretches thence in a broad tract southwestward
the Great Lakes, and thence northwesterly to the Ar
of the Mackenzie valley. This general statement is to
observing that formations of the Proterozoic era oc
tracts within this area, and that many of them have not
from the Archean. A few small areas of still later fo
the Archean at certain points within this tract, but
underlies such formations at no great depth, the ge
made above is not seriously incorrect. This Canadia
likened to a great "V" or "U" with its apex resting o

[1] The literature on the Archean (as well as Algonkian [Pro
America was summarized by Van Hise in Bull. 86, U. S. Geol. S
publication gives full bibliography to its date. A later (1896) a
of the same subjects by the same author was published. Pt. II, 16t
Geol. Surv., pp. 744–843. The pre-Cambrian literature since 1
marized from time to time by the same author, and by Leith, in
as follows: Vol. I, pp. 304 and 532; II, pp. 109 and 444; III, p
pp. 362 and 744; VI, pp. 527, 739, and 840; VII, pp. 190, 406, 702, a
IX, pp. 79 and 441; and XII, pp. 63 and 161.

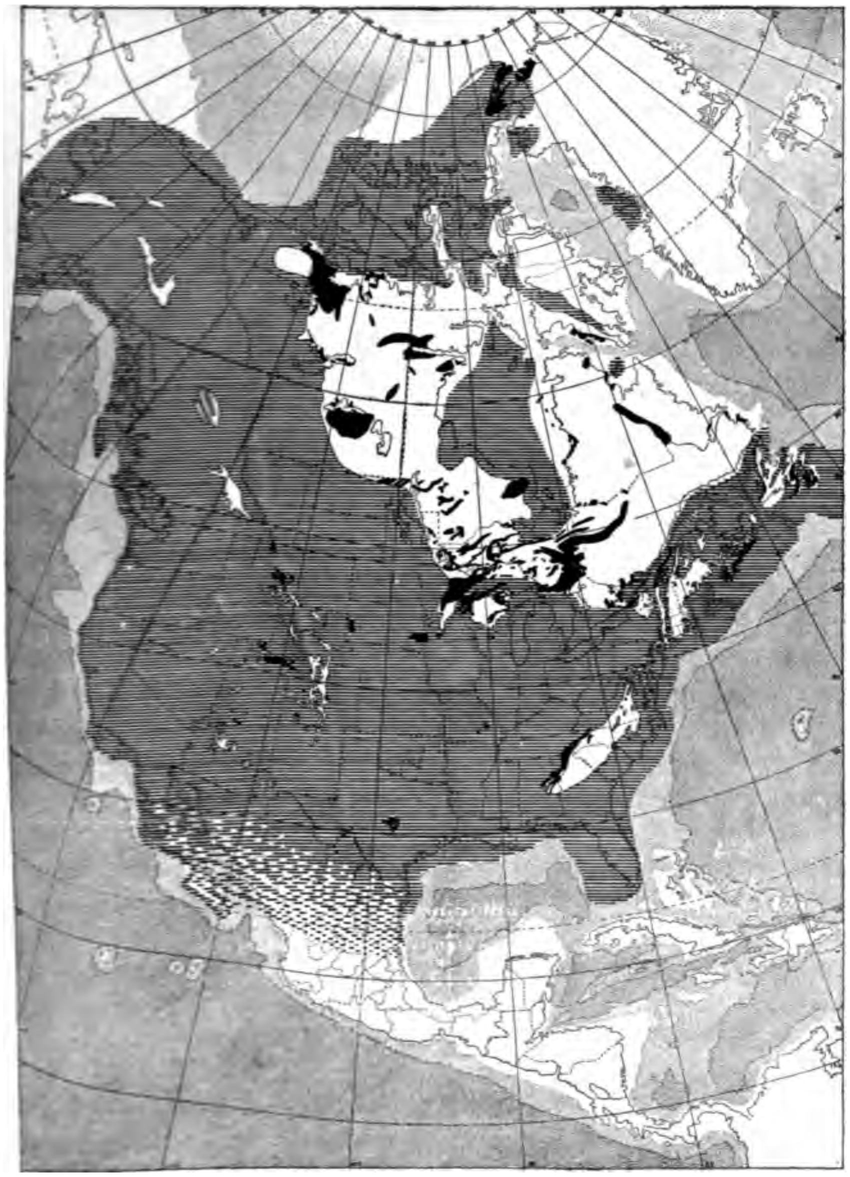

FIG. 38.—The white areas north of Mexico represent exposures of Archean with some undifferentiated Proterozoic; the white areas south of the United States represent lack of knowledge; the black areas represent exposures of Proterozoic, while the lined areas represent Archean or Proterozoic, beneath later formations. The light shading about the borders of the land represents the area of the continental platform covered by sea-water, or what is the same thing, the area of the epicontinental sea for this continent.

and its arms embracing the Hudson Bay basin, but very accurate. The distribution may be seen in tr greater detail on the accompanying map (Fig. 38), in areas indicate Archean rock at the surface, the black rocks, and the lined areas either Archean or Protero lying later formations. As indicated above, the A believed to underlie all later formations everywher areas of the map are intended to represent only th are believed to have constituted a part of the cont and not improbably were exposed at some time as l understood that this map is no more than a roug representative of the present stage of mapping an Closely related to this great Canadian area are tracts Wisconsin, in Minnesota, and in the Adirondack regi though at least some of the rocks of this last reg younger (Proterozoic).

Lying rudely parallel to the great Canadian area is a broken series of probably Archean tracts exte foundland to Alabama. Similarly, on the southw a belt of detached areas stretching from New Mexi few places within these belts have the ancient rock great detail.

Greenland, so far as can be judged from its k occupied by crystalline rocks of probable Archean a may be said of large tracts imperfectly known on Baffin bay.

Partly because of the inherent difficulties, an of the inaccessibility of a large part of this great Arc detailed work has as yet covered but a small part o of Lake Superior in Canada, Michigan, Wisconsin (Fig. 39), the original Huronian area north of Lak Ottawa region in Ontario, have been the classic area

Local development.[1]—A definite conception of the chara is best obtained by the study of its local development in

[1] In addition to the references given in connection with the the Archean appears on the maps of the following folios of t *Arizona*, Globe and Bisbee; *Colorado*, Ten Mile, Anthracite-C Walsenburg, and Pike's Peak; *District of Columbia*, Washington

have been investigated in some detail. The following brief statements concerning the rocks of the system at selected points may be supplemented by the study of the original treatises referred to.

In the *Marquette region* of northern Michigan, the Archean consists of (1) the *Keewatin*, Mona, and Kitchi schists (metamorphosed lavas and tuffs), with which are associated serpentines and dolomites (both derived in part from peridotites), and (2) the *Laurentian*, gneissic granite and more or less syenite, intrusive in the schists. These rocks are affected by numerous dikes and bosses of diabase, basalt, and granite.[1] A section showing the relations of the Archean to the Proterozoic rocks in this region is given in Fig. 40.

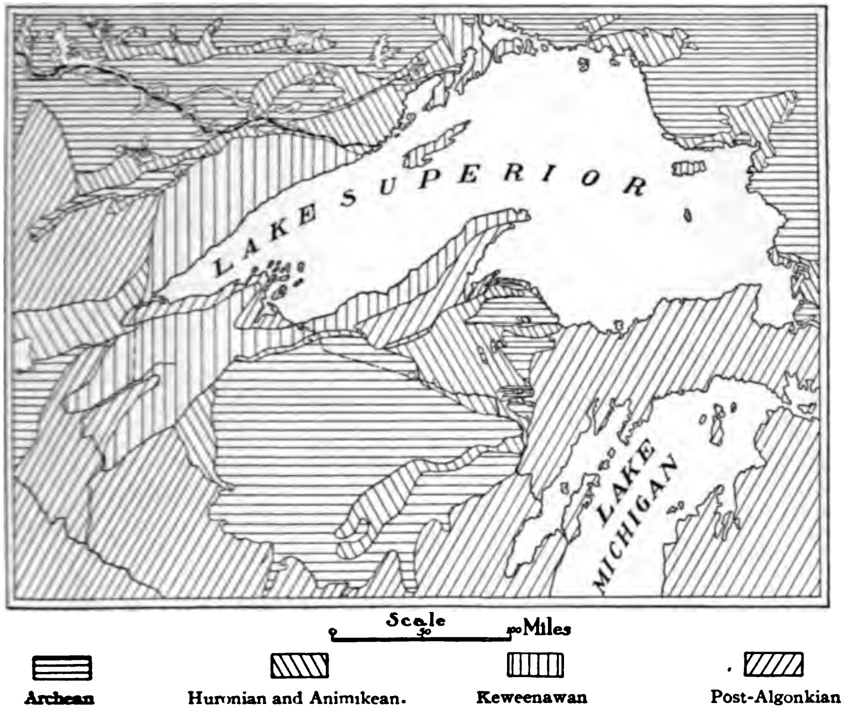

Fig. 39.—Map of the Lake Superior region showing the distribution of Archean, Huronian, Animikean, Keweenawan, and post-Proterozoic formations. (Van Hise and Leith, U. S. Geol. Surv.)

In the *Menominee region*, a little farther south, the Archean consists of (1)

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nee: *Montana*, Fort Benton, Little Belt, Three Forks, and Livingston; *North Carolina–Tennessee*, Asheville and Cranberry; *Tennessee–North Carolina*, Greenville; *Wyoming*, Absaroka and Yellowstone.

[1] Van Hise, 15th Ann. Rept., U. S. Geol. Surv., pp. 517-589, and Van Hise, Bayley and Smyth, Mono. XXVII, U. S. Geol. Surv.

Keewatin, greenstone schists and spherulitic greenstone, cut b diabase, and granite, and schistose quartz-porphyry (Quinn

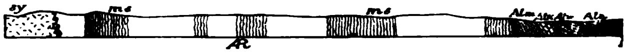

FIG. 40.—Figure showing the structure of Archean and Huronia locality in the Marquette region of northern Michigan. The are: *sy*, syenite, and *ms*, Mona schist. The Huronian format nard quartzite; *Alk*, Kona dolomite; *Alw*, Wewee slate; *Al* *Als*, Siamo slate; and *Aln*, Negaunee formation (iron-bearing). 3 miles. (Van Hise, U. S. Geol. Surv.)

and (2) *Laurentian*, granites, gneisses, hornblende, greenston above. The lower division is similar to the schists of the Ma represents metamorphosed igneous rocks of diverse origin (flows

In the *Mesabi district* of northeastern Minnesota [2] the Arc cipally of various greenish rocks (*Keewatin*), including dolerit micaceous and chloritic schists, with spherulitic structures co massive portions, all of igneous or meta-igneous origin. Wi there are some granites and porphyritic rhyolites.

In the *Vermilion district*,[3] the Archean consists of (1) *Keew* stone, and the Soudan formation, and (2) *Laurentian* gra altered extrusive rock of andesitic and basaltic types. I spherulitic and amygdaloidal structures, but they are larg Soudan formation is meta-sedimentary, consisting of basal co from the Ely greenstone below, and an iron-bearing portion consists of banded white chert, red jasper, carbonate-beari magnetite schist, magnetite, pyrite, and hematite. Iron or Archean is extensively mined in this region. The original were the carbonate and the silicate (sedimentary). Its ch (chiefly hematite), and its concentration, as now found, w

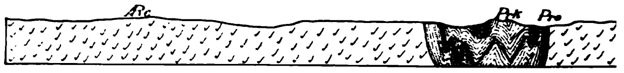

FIG. 41.—Figure showing the relations of the Archean and Huroni in the Vermilion district. Archean formations: *ARe*, Protero Ogishkee conglomerate, and *Prk*, Knife Lake slates. Lengt miles. (Clements, U. S. Geol. Surv.)

quently[4] (see Iron Ores, Chapter IV). The granites are in greenstone and the Soudan formation.[5] Figs. 41 and 42

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[1] Van Hise and Bayley, Menominee folio, U. S. Geol. Surv. XLVI, U. S. Geol. Surv.

[2] Leith, Mono. XLIII, U. S. Geol. Surv.; Winchell, Geol. s of Minn., Vol. IV.

[3] Clements, Mono. XLV, U. S. Geol. Surv.

[4] Van Hise, 21st Ann. Rept., U. S. Geol. Surv., Pt. III.

[5] Leith, Mono. XLIII, U. S. Geol. Surv.; Minn. Geol. Surv.,

of the several members of the Archean to one another and to the Proterozoic in certain parts of this region.

In the *Rainy Lake and Lake of the Woods districts* of Canada, the Archean consists of (1) *Keewatin*,[1] metamorphosed basalts, diorites, and other basic igneous rocks, associated with narrow bands of carbonaceous slate and limestone,[2] (2) *Laurentian* granites and gneisses intrusive into the Keewatin.

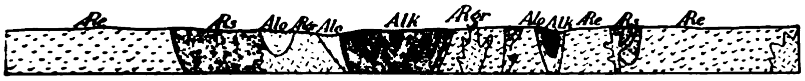

FIG 42.—Figure showing the relations of Archean and Huronian formations in another locality in the Vermilion district of Minnesota. Archean formations: *Ægr*, Archean granite; *Æs*, Soudan formation; *Æe*, Ely greenstone. Proterozoic formations: *Alo*, Ogishkee conglomerate; *Alk*, Knife Lake slates. Length of section, about 5 miles. (Clements, U. S. Geol. Surv.)

The Archean complex, *Keewatin and Laurentian*, is also found on the north shore of Lake Huron, where it is overlain by pre-Cambrian rocks, chiefly sedimentary,[3] and again in the vicinity of Ottawa, where it is composed mainly of granitoid gneiss (Ottawa gneiss).[4] It is also known at various points about Hudson bay,[5] and between it and the Cambrian formation above there are two, and in some places three, great series of clastic rocks separated by unconformities. Throughout all this northern region the relations of the Archean to other formations are usually intricate.

The Archean in the great *southeastern belt* has been studied in detail in a few localities. In the vicinity of Washington,[6] D. C., the rocks classed as Archean include gneisses, schists, granite-gneisses, diorites and meta-diorites, gabbros and meta-gabbros, soapstone (altered peridotite and pyroxenite) and granite. Something of their relations is shown in Fig. 43. In an area of *western North Carolina* [7] where the rocks have been carefully studied, the Archean is divided into five or six formations, made up mostly of gneisses and schists (Fig. 44).

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[1] Lawson, Geol. Surv. of Canada, Vol. III, Pt. I, F, 1887-8, pp. 99, 100, and 105. Lower Keewatin = Ely greenstone and Soudan formation of the Vermilion region.

[2] Coleman, Bull. Geol. Soc. Am., Vol. IX, p. 224. Coleman considers the Lower Keewatin to correspond to the Lower Huronian (= Huronian of this Vol.), Rept. Ontario Bureau of Mines, 1900, p. 186.

[3] Logan, Rept. of Progress of the Geol. Surv. of Canada from its commencement to 1863. Bull. 86 and 21st Ann. Rept., U. S. Geol. Surv., Pt. II. Full bibliography given in Bull. 86, up to 1892. The 18,000 feet probably includes some Keewatin.

[4] This is the original Laurentian area. The rocks were formerly known as the Lower Laurentian. Logan, Rept. of Geol. Surv. of Canada, for 1845-46, pp. 40-51.

[5] See reports of Geol. Surv. of Canada.

[6] See references in Bull. 86, U. S. Geol. Surv.; and Keith, Washington (D. C.) folio, U. S. Geol. Surv.

[7] Keith, Cranberry (N. C.-Tenn.) folio, U. S. Geol. Surv.

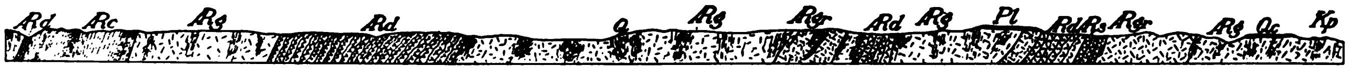

FIG. 43.—Section showing the relation of the Archean and younger formations in the vicinity of Washington, D. C. Archean formations: *Æc*, Carolina gneiss; *Ægr*, granite; *Ædr*, diorite; *Æs*, serpentine; *Æg*, gneiss. Younger formations: *Kp*, Potomac formation (Cretaceous); *Pl*, Lafayette formation (Pliocene); *Q* and *Qc*, Columbia formation. Length of section, 9½ miles. (Keith, U. S. Geol. Surv.)

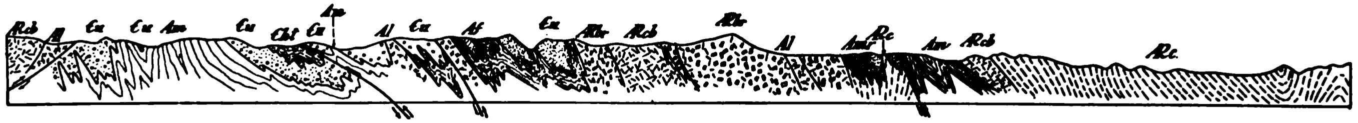

FIG. 44.—Section showing the relation of the Archean and Proterozoic rocks in western North Carolina. Archean formations: *Æc*, Carolina gneiss; *Æcb*, Cranberry granite; *Æbr*, Blowing Rock gneiss. Proterozoic formations: *Al*, Linnville metadiabase; *Am*, Montezuma scnist; *Af*, Flattop schist; *Amr*, metarhyolite. Younger formations: *€u*, Unicoi formation (Cambrian); *Cht*,

Some members of the series are clearly intrusive in others, and therefore younger. The older members show profound metamorphism. In the older formations a first dynamic movement developed foliation in rocks which were originally igneous, while a second folded the planes of foliation. Two profound metamorphic movements are thus recorded.

The Archean of the great western belt has similar characters. In the Grand Canyon of the Colorado, in northern Arizona, the same types of rock (the Vishnu terrane [1]) are exposed. They are separated from the Cambrian by the Grand Canyon system,[2] itself divisible into two series by an unconformity,[3] the upper being unconformable below the Cambrian.

The relations of the Archean at various other points in the west are illustrated by Figs. 45 to 48.

The structure of the Archean system is usually more complex than would be inferred from any brief descriptions, such as those given above. It would indeed be difficult to obtain an exaggerated idea of the complexity of the relations of the various sorts of rock which have caused this system to be called variously the "Archean complex," the "basement complex," the "fundamental complex," etc.

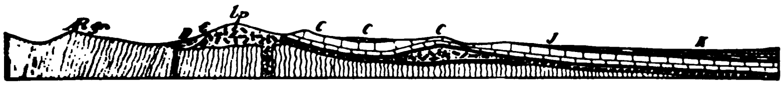

FIG. 45.—Section showing the relations of the Archean to other formations near Fort Benton, Montana. *ÆRgn*, Archean gneiss; *Ꞓ*, Cambrian; *D*, Devonian; *C*, Carboniferous; *J*, Jurassic; *K*, Cretaceous; *bp*, Barker porphyry. Length of section, about 21 miles. (Weed, U. S. Geol. Surv.)

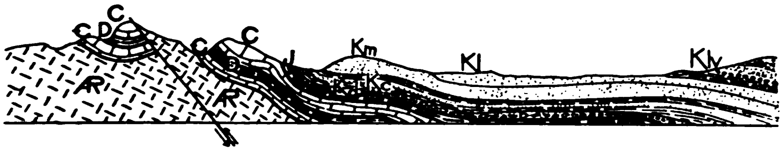

FIG. 46.—Section showing the relation of Archean to younger formations near Livingston, Montana. *Æ*, Archean; *Ꞓ*, Cambrian (Gallatin limestone); *D*, Devonian (Three Forks shale and Jefferson limestone); *C*, Carboniferous (Madison limestone and Quadrant quartzite); *J*, Jurassic (Ellis formation); *Kd*, *Kc*, *Km*, *Kl*. and *Klr*, Cretaceous (Dakota, Colorado, Montana, Laramie, and Livingston, respectively). Length of section, 11 miles. (Weed, U. S. Geol. Surv.)

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[1] Van Hise, Bull. 86, U. S. Geol. Surv.; and Walcott, 14th Ann. Rept., U. S. Geol. Surv., Pt. II, p. 506.

[2] Powell, U. S. Geol. Surv., and Geog. Surv. of the Territories; Rept. on the Geology of the Eastern Portion of the Uinta Mountains, 1876, p. 70.

[3] Walcott, 14th Ann. Rept. U. S. Geol. Surv., Pt. II, p. 506. The Vishnu of Walcott appears to be Archean, leaving only the Unkar and the Chuar divisions of the Grand Canyon series between the Archean and the Cambrian.

By way of summary it may be said that the system places of rocks which are mainly massive (igneous);

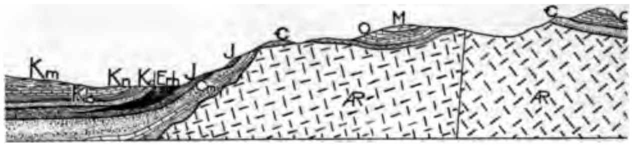

FIG. 47.—Section showing the relations of Archean to younger Crested Butte region of Colorado. *Æ*, Archean; *Є* Cambria ite); *O*, Ordovician (Yule limestone); *M*, Mississippian (L *Cw* and *Cm*, Carboniferous (Weber and Maroon formations, re rassic (Gunnison formation); *Kd*, *Kb*, *Kn*, and *Km*, Cretaceo Niobrara, and Montana, respectively); *Erh*, Eocene rhyolite. 6 miles. (Eldridge, U. S. Geol. Surv.)

of rocks which are mainly gneissic (chiefly meta-ig still others, of rocks (largely meta-igneous and subo sedimentary) in which a schistose structure predominate the rocks of each of these structural types have a wid position, from acid on the one hand to basic on th of all these classes are often intimately associated, and a dominate over the others to varying extents. In some of these several structural types graduate into one anoth as to leave no line of separation, while in others th sharp. Thus massive rock sometimes appears in w which cut the gneisses and schists at any angle, while o schists are frequently in dike-like sheets in rocks whic sive. In the first of these cases, the gneissic or schis incloses the dikes of massive rock probably suffered before the intrusion of the latter, which has never be

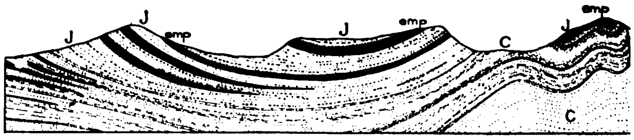

FIG. 48.—Section showing the relation of the Archean to younge Ten Mile district of Colorado. *Æ*, Archean; *C*, Carbonif *emp*, Elk Mountain porphyry. Length of section, 4 miles. Geol. Surv.)

the second, the inclosing rock was not metamorph intrusion, and in the changes of subsequent time th was the more altered. Furthermore, the relations of these several sorts of rock have been enormously complicated by the distortion to which they have been subject. The structure and relations of the several sorts of rock in the system indicate that it was (1) by successive intrusions, large and small, of rocks of different chemical composition, into (2) still older rocks which were originally (*a*) chiefly extrusive-igneous and of varying chemical composition, but (*b*) subordinately sedimentary, and (3) by successive dynamic movements resulting in various degrees of metamorphism and deformation of the various parts, that the intricate structure and composition of the Archean complex was attained.

While, therefore, the variations in the rock of the Archean complex are great, there is, nevertheless, a certain homogeneity in the heterogeneity of the whole. No one considerable part of the system is very different from any other considerable part, and no definite and orderly relationship between the different parts has been made out over any considerable area. There appears to be no traceable succession of beds, and no definite stratigraphic sequence, such as can be made out in great series of meta-sedimentary rocks, however much folded and metamorphosed. So similar are the rocks of the Archean throughout the various areas where the system occurs, that a suite of unlabeled specimens from one region could hardly be asserted not to have come from any other.[1] This striking similarity affects not only the general features of the rocks concerned, but also many of the details of their structure and composition. The minerals of which they are composed everywhere (broadly considered) give evidence of having been subject to great dynamic action. They are often broken and distorted, and microscopic study reveals the effects of dynamic action in many cases where it is not visible to the unaided eye. The mineralogical and chemical constitution of the series, taken as a whole, appear to be essentially constant, in the sense that the variations in any one area are very much the same as those in any other.

Bearing of the Archean on the theory of the origin of the earth.—If any accessible system of rocks can be made to throw light on the origin and early history of the earth, it is the Archean. With the essential facts concerning the constitution and structure of the system in mind, it is in order to inquire to what hypothesis of the earth's origin

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[1] Van Hise, Bull. 86, U. S. Geol. Surv., p. 476.

they best adjust themselves. The constitution of the
it clear that it does not represent the original crust of t
downward extension. It cannot be affirmed, however,
of what is now classed as Archean is referable to the
that is, it cannot be affirmed that no part of the igneous c
rock of the Archean is referable to an azoic or pre-zoic
as the evidence against such reference may seem. On t
all the facts now known concerning the Archean adj
to the planetesimal hypothesis, or to the modified forn
molten hypothesis. They cannot, however, be said to e
or to preclude other hypotheses of the origin of the earth.
of the origin of the Archean must, therefore, still be
open one. According to the planetesimal hypothesis
is looked upon as representing the time of transition f
Formative eon to the later Gradational eon (p. 119).
the modified form of the gaseo-molten hypothesis, it
formations of the volcanic era which followed the fo
original crust.

Earlier Views Concerning the Archean.

In explanation of the Archean system, many differ
have been suggested at one time and another, most o
with the Laplacian hypothesis as a beginning. Some of
ses have at least a historic interest. One is that the Ar
completely metamorphosed sediments; a second, that t
rocks produced by the fusion of sediments; and a thir
igneous rocks intruded beneath the oldest known sed
after the deposition of the latter.

1. The hypothesis that the Archean rocks are
sediments was originally based on the assumption that
gneissic structure were an expression of stratification
everything which resembles stratification is really suc
this view obtained, it was natural that the gneisses and
be regarded as of sedimentary origin; but since it is n
such structures may be developed in sedimentary roc
of stratification, and in igneous rocks as well, the arg
force.

If the Archean rocks are primarily metamorphose would seem that there should be somewhat wide-spread evidence of the fact in the structure of the system. So thick a series of sediments would surely have been made up of layers of varying physical and chemical composition. From such a series, no matter how completely metamorphosed, it is not probable that the original distinctions of constitution would have been generally obliterated; but in most of the Archean, no such succession of strata as would be expected if the rocks were dominantly meta-sedimentary exists. This point has special force when it is remembered that it holds not for one region only, but for each of the many regions, some of them of great extent, where the Archean rocks have been studied. It would appear that such effective and wide-spread obliteration of the characteristics of sedimentary rocks could only have been brought about by their fusion; and in this case the product, on solidifying, should no longer be regarded as metamorphic rock, but as igneous rock instead.

A special phase of this hypothesis makes the Archean the altered product of a chemical precipitate from the original ocean. This hypothesis never met with general favor, and has rarely been seriously entertained.[1]

2. A second hypothesis which has been advanced is that the Archean, at least locally, consists of igneous rock produced by the fusion of deeply buried sediments.[2] If this hypothesis were true, the igneous rocks produced by the fusion of sediments should grade up into sedimentary rocks above; they should not be separated from them, as they generally are, by an erosion unconformity. Otherwise it would be necessary to suppose that the lower igneous series was fused long before the upper series was deposited, and that the beds which originally overlay the igneous series, and which were not fused, were subsequently removed by erosion before the deposition of the existing superior, unconformable, sedimentary series. While this sequence of events could not be disproved for certain localities, it is not probable that it represents the general history of most regions where the Archean occurs.

3. A third hypothesis is that the Archean represents igneous rock

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[1] Hunt, The Taconic Question in Geology and the Origin of Crystalline Rocks Trans. Roy. Soc. Canada, Vols. I and II. The untenability of this hypothesis was shown by Irving, 7th Ann. Rept. U. S. Geol. Surv., p. 383.

[2] Lawson, Ann. Rept. Canadian Geol. Surv., 1887.

intruded beneath the sedimentaries after the deposition and that they were brought into their present litholog by metamorphism subsequent to their irruption. Th is distinct from the last in that it involves the intrusion rock, rather than its formation *in situ*, and in that it do that the source of the lavas was sedimentary rock. It i ceding in that it makes the Archean a meta-igneous the sedimentary rocks overlying the Archean do not, as the contact metamorphism which this hypothesis demar the unconformity between the two series is generally an of erosion, not of irruption, the hypothesis fails to expl Furthermore, the hypothesis, as a general explanation of is an audacious one, for it supposes that igneous intrusic in at the base of the known sedimentary series, not in o but generally where the base is accessible, thus commo the floor on which the oldest sediments were deposite an assumption makes the hypothesis based upon it imp

Though the hypothesis can hardly be accepted as a ge tion of the Archean, it does not follow that the oldes rocks nowhere rest, with irruptive unconformity, on ig

The Archean in other countries.—The general c relations of the Archean complex already given for N seem to be duplicated in other continents. Correspond rocks, made up primarily of meta-igneous, but subordir tricably involved meta-sedimentary rocks, are known in The general characteristics and relations of the Archean in North America, therefore appear to be essentially w

In Great Britain, the Lewisian gneiss appears to cc the Archean of North America. This formation was d chanical deformation from a complex aggregate of eru different ages, and in one area there appears to be a grou ancient sedimentary rocks through which the gneiss wa

In Norway, coarse-banded gneisses (Grundfjeldet, U a wider petrographic range than the Lewisian gneiss of are regarded as Archean. The gneisses seem to have o acidic and basic eruptive rocks. With the gneiss is asso

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[1] For review of this hypothesis, see Van Hise, Bull. 86, U. S. G

[2] Geikie's Text-book of Geology, 4th ed., Vol. II, p. 888.

group of rocks of meta-sedimentary origin affected by dikes and sills of igneous and meta-igneous rocks.[1]

The Archean rocks of Sweden[2] and Finland,[3] as now interpreted, are similar to those of Norway. They consist of meta-igneous and meta-sedimentary rocks, among which is limestone, together with some igneous rocks not notably metamorphosed.

In France, the Archean is composed chiefly of gneisses and schists of various types, chiefly or wholly meta-igneous.[4]

In Bavaria, the rocks classed as Archean consist of gneiss (Bojan) remarkable for its uniformity, and of schists and gneisses (Hercynian) which include meta-sedimentary beds, among which is graphitic limestone.[5]

In Spain, gneisses and schists which include some limestone beds (Cipollino = limestone with scales of mica, talc, etc.) are commonly classed as Archean.[6]

Similar rocks regarded as Archean occur in India[7] (Bunkelkund gneiss); in northern China,[8] where the Archean has not been clearly differentiated; perhaps in Japan;[9] in Australia,[10] where gneisses, schists, and meta-sedimentary beds classed as Archean lie at the surface, over an area some 20,000 square miles in extent; in Tasmania;[11] and in New Zealand.[12]

Life during the Archeozoic era.—The presence of carbonaceous material, of bedded iron ores that were once carbonates, of cherts, and probably of limestones, implies the presence of life occupied in the formation of the Archean rocks. Since been found, nothing is positively known of the chara and little, except by inference, of its abundance.

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[1] Reusch, Die Fossilführenden krystallinischen Schiefer von Bergen, 1883, and Neues Jahrbuch (Beilage-band), 1887.

[2] Torneböhm papers in Geol. Fören, Stockholm; in Handl. Akad. Stockholm, Vol. XXVIII, 1896; and in reports of the Sverig. Geol. Undersökn.

[3] Sederholm, Bull. Com. Geol. Finlande, 1899; also same author's papers in Tschermak's Mittheil., Vol. XXII, 1891; Fenia, Vol. VIII, 1893; Geol. Fören, Stockholm, XIX, 1897.

[4] De Lapparent, Traité de Géologie.

[5] Gümbel, Geognostische Beschreibung des Oberbayerischen Grundgebirges, Gotha, 1868. Cited by Geikie, Vol. II, p. 801.

[6] De Lapparent, Op. cit.

[7] Medlicott and Blanford, Manual of Geology of India.

[8] Von Richthofen, China, Vol. II.

[9] Koto, Jour. Coll. Sci., Imp. Univ. of Tokyo, Vol. V, 1893, Pt. III.

[10] David, Proc. Linn. Soc. N. S. Wales, Vol. VIII, 1894.

[11] Johnston, Geology of Tasmania, 1888.

[12] Hector, Handbook of New Zealand, 1883; Haast, Geology of Canterbury; and Hutton, Geology of Tago.

Duration of the Archeozoic era.—Of the duration of era nothing can be said beyond the general statement great, and this conclusion is independent of any partic of the earth's origin. If the planetesimal hypothesis there is no readily assignable lower limit to the Archeoz the duration of the Archeozoic era may exceed that o time.

For convenience of future reference, a table of th logic time-divisions is here added:

General Table of Geologic Time Divisions.

Cenozoic	Present.	
	Pleistocene.	
	Pliocene.	
	Miocene.	
	Oligocene.	
	Eocene.	
	Transition (Arapahoe and Denver).	
Mesozoic	Upper Cretaceous.	
	Lower Cretaceous (Comanche or Shastan).	
	Jurassic.	
	Triassic.	
Paleozoic	Permian.	
	Coal Measures, or Pennsylvanian.	
	Subcarboniferous, or Mississippian.	
	Devonian.	
	Silurian.	
	Ordovician.	
	Cambrian.	
	Great Unconformity.	
Proterozoic	Keweenawan.	
	Unconformity.	
	Animikean. (Upper Huronian of some aut	
	Unconformity.	
	Huronian. (See p. 161.)	
	Great Unconformity.	
Archeozoic	Archean Complex.	Great Granitoid Series. (Intrusive in the mai
		Great Schist Series. (Mona, Kitchi, K sec; Lower Hu authors.

The following classification of the pre-Cambrian has recently been proposed by a Committee of the United States and Canadian Geological Surveys appointed to consider the question:

CAMBRIAN—Upper sandstones, etc., of Lake Superior.
  Unconformity.
PRE-CAMBRIAN.
  Keweenawan (Nipigon).
    Unconformity.
  Huronian.
    Upper (Animikie).
      Unconformity.
    Middle.
      Unconformity.
    Lower.
    Unconformity.
  Keewatin.
  Eruptive contact.
  Laurentian.

The Lower and Middle Huronian of this table,[1] taken together, correspond to the Huronian of the table above. This classification was published after this chapter was in the hands of the printer, and has therefore not received, in the pages which follow, the consideration to which its history entitles it. It will be noted that its principal departure from the preceding classification lies in the threefold, instead of twofold, division of the rocks between the Archean below, and the Keweenawan above.

[1] Jour. of Geol., Vol. XIII, p. 104.

CHAPTER IV.

THE PROTEROZOIC ERA.

To the Proterozoic[1] era is assigned the time between
formation of the igneous complex just described, and t
the lowest system which is now known to contain abu
served fossils; or in other words, the time between t
Archean and the beginning of the Paleozoic. During
era several great series of sedimentary formations,
with one another, were formed (p. 160). These sedi
were rather freely interlarded with igneous sheets, some
intruded as sills, and some spread upon the surface w
beds were being formed. It was therefore a time when i
was still rather pronounced, though by no means so
dominant as in Archean times. Sedimentation had b
first time, the leading process in the formation of the ge

In contrast with the Archeozoic, the dominant featu
and the feature which was really most significant in th
earth, was the effectiveness of the weathering proces
hydro-atmospheric work upon the land which furnish
for sedimentation. These processes were really more
the sedimentation, because they were prerequisites t
turn, were dependent on the deformations of the body of
gave the topographic conditions necessary for erosion,
pheric and thermal conditions. The sedimentary
era, however, constitute the main part of its record, an
pal subject of geologic investigation.

The Proterozoic rocks include the first great series
imply mature weathering, and the prolonged and conti
in the sea of weathered material derived from the adjac

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[1] Proterozoic, as here used, is a synonym for *Algonkian* as used
Surv.

important to emphasize the inauguration of the reign of these processes, for they have been the dominant ones ever since. It is not to be overlooked, however, that the vulcanism which had predominated in the Archean era was still a factor, though a declining one. Locally it still made larger contributions than sedimentation to the formations of the era, and such has been its habit in all later times. But, taken as a whole, Proterozoic times, as the descriptions of the formations will show, were marked by more igneous activity than the Paleozoic, Mesozoic, or Cenozoic eras that follow, and the Proterozoic may therefore be regarded as a transition-time between the profoundly igneous era that preceded, and the markedly sedimentary eras that followed.

Stratigraphic Relations of the Proterozoic Rocks.

The Proterozoic series are generally separated from the Archean below and from the Paleozoic above by unconformities (Vol. I, p. 18). Unconformities vary greatly in extent and significance. Great unconformities usually involve three elements: First, a change of attitude in the lower formation, as the result of which it is subject to erosion; second, a period of erosion during which its upper part is truncated; and third, another change resulting in the deposition of the upper series on the eroded surface (Figs. 49 and 50). In some cases the unconformity may be due, theoretically, to a withdrawal and return of the sea, or to a lifting and subsidence of the land, or to both acting in coöperation. But if the beds below the unconformity are deformed, it is obvious that more than mere change of level was involved. In most cases the unconformity between the Archean and the Proterozoic systems indicates that the former was notably deformed, and afterwards subjected to prolonged erosion, before the deposition of the latter It is usually an invasion of the sea which furnishes the conditions

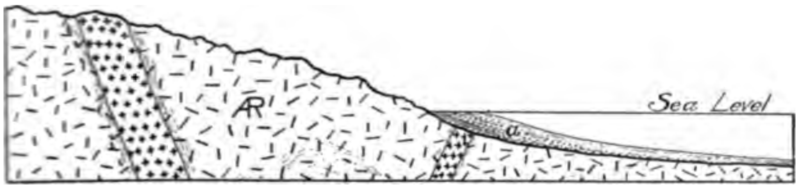

FIG. 49.—Diagram showing Archean land (Æ) with sedimentation, *a*, along its borders. The coarser sediments are being deposited near the shore; the finer, farther from it. (Compare Fig. 50.)

deposition, particularly where the deposits form a wi thick series; but this is not necessarily the case, for l take place in interior basins and on low gradation-pla systems as the Proterozoic, where fossils are generall cannot be asserted that the sea was involved, though th favor a marine origin for most of the sediments.

Though the Proterozoic rocks are generally unconfo Archean, unconformity between the two systems cann to exist at every point where their contact has been see ever, so general as to show that wide-spread changes of ably warpings of the crust) took place after the for Archean, and before the formation of the known Prote lapses of time were doubtless involved in these chang history of the interval recorded by the unconformity

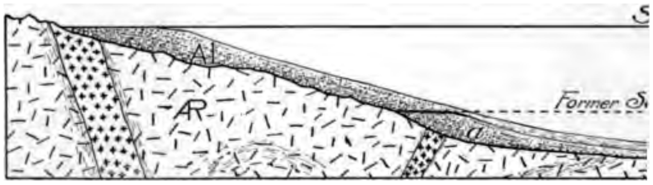

Fig. 50.—Diagram representing the same region as Fig. 49, after subs this figure corresponds to *a* of Fig. 49. It is to be noted th overlie the coarse sediments deposited at an earlier time in th of the figure.

more than conjectural knowledge. It is clear, howev unconformity exists, the Proterozoic beds above the are not the oldest sedimentary beds derived from th the material removed from the eroded Archean surface somewhere, and that before the beds immediately ab of unconformity were laid down.

While unconformity between the Archean and t is the rule, so far as their contacts are known, it shoul such unconformity is presumably not universal. There places, even on the land-areas, where the surface of tl not suffer notable erosion before the deposition of Proter upon it, and there were quite certainly such places in tinuously covered by the sea. Relations of conformit two systems may therefore exist over great areas whe is not exposed, and perhaps in some places where it

A sequence of events which might have given rise to the unconformable relations of the Archean and the Proterozoic, where seen, is illustrated by Figs. 49 and 50. Fig. 49 represents an area of land composed of Archean rock in such a position as to suffer erosion. The sediments derived from it are washed down to the sea and deposited in its waters (*a*). In Fig. 50, the land of the preceding figure is represented as having sunk so as to be partially submerged. A part of the sediments washed down from the remaining land are being deposited on the surface which formerly suffered erosion. These sediments (*Al*, Fig. 50) overlie those deposited at the earlier stage. The latter (*a*) are the older, though the former may be the oldest now accessible.

Subdivisions.

No classification of the formations of the Proterozoic era has been widely accepted as of general application, but where these rocks are best known, at least three great unconformable series or systems are referred to this era. These several divisions are of such thickness and extent that their local names may well be taken for the great subdivisions of the rocks of this era. In the order of age, these systems are (1) the Huronian, (2) the Animikean or Penokean, and (3) the Keweenawan (p. 160). The first system is named for the region north of Lake Huron, where the rocks were first differentiated. The names of the second system come from localities in northeastern Minnesota and northwestern Wisconsin respectively, where the rocks are well developed, while the name of the third system is derived from the Keweenaw peninsula of northern Michigan, on the south shore of Lake Superior.

Each of the systems in this region measures thousands of feet in thickness, but it is important to note that, thick as they are, they do not constitute a complete record of the Proterozoic era. The unconformities between them show that, after the formation of each, there was a disturbance of relations between the sources of the sediments (the lands) and the sites of their deposition (chiefly the sea). Each unconformity appears to mark a prolonged period during which erosion was in progress in the region where the formations are exposed, and deposition somewhere else. The sediments deposited at this time are probably buried under later formations, either within the continent or about its borders, and remain inaccessible. The intervals represented by the unconformities are *unrecorded*, so fa strata are concerned, though they are recorded by the u themselves. It is not impossible that the interval represent formity in one region is represented by known strata in in the absence of fossils, this relation is difficult of d Whether the stratigraphic records made in these interv identified or not, they must be taken into account in th of the Proterozoic era as a whole. This era therefore time when at least three thick systems of strata were de two intervening intervals, represented by unconformit now known to be recorded by accessible strata. Nor is unconformities between the Proterozoic formations and on the one hand, and between the Proterozoic and the the other, are to be taken into account. Some portion represented by each of these two great unconformities is t to the Proterozoic.

Proterozoic Sedimentation.

General considerations.—The stratigraphic relations of the Proterozoic formations to the Archean show that they we on the bed of a sea, or other lodgment area, which, at the the formations are known, was advancing upon the la time of the advance of the Proterozoic seas (taken as repr all lodgment areas) upon the lands of Archean rock, t the latter was probably comparable to existing land surf talline rock which have been long exposed to weatherin phases of erosion. The topography was doubtless more or and the surface mantled by soil and residual earths (regolith, geest) which had arisen from the decomposition lying rock (Vol. I, p. 41). Large and small masses of rock, ant than their surroundings, probably remained undecom partially decomposed, in the earths which represented th more complete decay.

The general nature of the clastic sediments laid down o surface when it was converted into an area of deposi readily inferred. They were made up chiefly (1) of the products already on the surface, (2) of the materials w rocks by the waves, and (3) of river detritus.

(1) **One of the first effects** of the Proterozoic seas, as they slowly transgressed the land—for it is presumed that this transgression was slow—was to work over, assort and re-deposit the loose material found on the surface. The larger masses of rock suffered relatively little transportation and wear; the sand and small bits of rock were rolled along the bottom and deposited in relatively shallow water, while the finer materials were carried out from the shore and deposited in the more quiet waters beyond (Vol. I, p. 369 et seq.). Deposits of gravel, sand and mud were doubtless being made at the same time at different distances from the shore, and from the gravel on the one hand, to the finest mud on the other, there were all possible gradations (Fig. 50).

Changes in the position of the shore line, and changes in the depth of water incident to the sinking of the land, may have brought about the deposition of fine sediment on beds of coarse material deposited at an earlier time (Fig. 50) when the water where they occur was shallow, and a return of shallow water, as by the rise or aggradation of the sea-bottom, may have caused coarse sediments to succeed the fine in vertical section. In such ways the sedimentary deposits came to be arranged in layers, coarser and finer alternating with one another in vertical section, and grading into one another laterally.

If, at all stages of the sinking which brought land composed of Archean rock below the Proterozoic seas, the waters found coarse and fine materials on the surface they transgressed, and if at all stages the finer parts were carried out from the shores, there should be a widespread deposit of coarse material (gravel) derived from the underlying rock at the base of the sedimentary series (Fig. 50). Such a formation is known as a *basal conglomerate*, and is often one of the best indices of an unconformity. All parts of a bed of basal conglomerate were not necessarily contemporaneous in origin. Thus the coarse material at *a* (Fig. 50) is older than that at *Al*, with which it is laterally continuous.

It is to be especially noted that the loose residual materials which the advancing Proterozoic seas found upon the surface which they transgressed had arisen chiefly by rock decay, and that they were therefore essentially unlike their parent formation in average composition (Vol. I, p. 422).

(2) Besides working over the regolith, the waves doubtless attacked the solid rock wherever exposures were favorable, just as waves here

and there cut into solid rock at the present time. The
derived resembled the parent formation in average com
are thus distinguished from those of the preceding clas
ments of this second class were more or less intimately
those which had been prepared in advance by the decomp
rock.

(3) The streams descending from the land brough
quota of gravel, sand, and mud. The larger part of th
detritus was probably made up of the decomposition pro
though a smaller part was probably derived by the mec
of running water on undecomposed terranes. Once in
detritus which the rivers brought down from the land wa
deposited with the sediments acquired in other ways.
minor quantities of terrigenous sediment were doubtles
the land to the sea, and added to that derived from the
ways.

Since much of the more soluble constituents of the
extracted during the processes of decomposition proba
in solution in the sea-water, it is to be presumed that th
ments were, on the whole, more siliceous than the rock fro
were derived.

The sorting power of moving water takes account o
conditions and properties of the materials handled, an
chemical constitution; but in the decomposition of
the quartz remaining in the residual mantle was gener
particles than the aluminous products of the decomp
silicates, and under the assorting influence of the wav
grains (sand) were more or less completely separated fr
nous particles (mud). Thus materials which were unl
were separated from one another because they were unl

If the Proterozoic seas harbored abundant shell-be
if their waters anywhere became overcharged with lime
solution, limestone might have been formed, and sho
associated with the other sedimentary strata.

Extent.—While the beds of sediment accumulated i
zoic are known in limited areas only, it is to be borne in
Proterozoic sediments were in reality as widespread as t
seas; for though coarse material from the land is not u

ut far from the shore, material fine enough to be carried in suspension may be transported great distances, and small amounts of dust are constantly being blown from the land to all parts of the sea. In later geologic time, the life of the sea has occasioned considerable deposits even far from the land, and presumably over the whole of the ocean bottom. The same may have been true from the beginning of the Proterozoic era, for the beginnings of life go even farther back. Both from extra-terrestrial sources, and by precipitation from solution, further additions may have been made to the sediments accumulating on the sea bottom. Sedimentation, even if slow, was therefore doubtless in progress in the deeper parts of the Proterozoic seas as well as near the shores. These general considerations prepare us for the study of the sedimentary rocks now exposed.

The sediments and their interpretation.—The sedimentary beds of the Proterozoic consist of conglomerates (Vol. I, p. 468), sandstones, Vol. I, p. 422), shales (Vol. I, p. 473), and limestones (Vol. I, p. 378), or of their metamorphic equivalents. Before being cemented or otherwise solidified into firm rock, their materials were gravel, sand, mud, etc. The manner in which such materials are now being derived from previous formations is set forth in Volume I, pp. 110–114, 332–338, and 420–426; the manner in which they are transported by streams, waves, and ocean currents is explained on pp. 115–119, 354, and 364 of the same volume; and the way in which they are assorted, distributed, and deposited is discussed on pp. 177–204 and 355–386. The facts and principles there set forth should be well in mind before the history of this and succeeding periods is studied. In so far as the Proterozoic sediments had the same characters as the modern sediments, it is inferred that they were formed in similar ways.

At the base of the Proterozoic, and at the base of its several systems, there are sometimes found beds of basal conglomerate, which, when traced laterally, are found to abut against steep slopes (cliffs) of the underlying formation. This is exactly the relation which the gravel and shingle of existing beaches sustain to the shore rock. It is therefore inferred that these ancient conglomerates represent ancient shore tracts. As the beds which overlie the basal conglomerates are usually of finer materials, the shore is inferred to have advanced upon the land as sedimentation proceeded, and thus to have given opportunity for the deposition of off-shore material over the coarse shore deposits

Conglomerate beds which are not basal also occur, and po in the conditions of sedimentation even where unconfor developed.

The Proterozoic group also contains great thicknesse which is composed chiefly of grains, and sometimes of quartz, cemented firmly together, usually by the seco of the grains, as explained and illustrated in Volume I is inferred therefore that in Proterozoic times there was tunity for the separation of quartz grains from the Archean rocks, and for the rolling and rounding of these they came to rest. As the quartzites of the Proteroz times thousands of feet thick, the decomposition which necessary sand must have been correspondingly great, great formations made of decomposable minerals (suc amphiboles, etc.) grains of quartz are absent or rare.

The Proterozoic formations also include great beds their metamorphic equivalents, which are interpreted products of the same decomposition, and their presenc inference drawn from the sandstones and quartzite also are present, from which it is inferred that the wat had become calcareous by processes similar to those no (Vol. I, pp. 429–431, 122, and 107), and that by one or processes by which limestone is now produced, a porti careous content of the waters was deposited. The lim further confirmation of the preceding inferences, for i position of crystalline rocks necessary to free the qua produce clays, the calcareous material is largely dissolv to the sea in solution.

The inference that these ancient sediments were de same manner as the sediments of modern times is fur by the ripple and other water-marks on the sandston and by the character of their lamination and stratifi where still preserved, are precisely analogous to those By combining evidences of this kind, until by mutu no rational room for doubt, the mode of form deposits is deciphered, and their history rea

The fact that some of the deposits are tell a different tale, tends rather to increas it. Some of the sandstones contain abundant grains of feldspar and other silicate minerals, from which it is inferred that the conditions under which their materials were derived did not permit mature decomposition. As the more notable sandstones (wackes) of this type are associated with lava beds, it is a consistent inference that as a result of the volcanic fragmentation that accompanied the outflows, and the naked surfaces that succeeded them, the ratio of surface wash to decomposition was high, and that fragmental material was borne away to the depositing grounds before being completely decomposed.

To account for the thick series of sediments which exist, it seems necessary to suppose that there was in progress, in some places at least, a slow, quiet warping of the surface which lowered the lodgment basins about as fast as they were filled, and perhaps at the same time raised the areas from which the supply of material came, though this last inference is not a necessary one (Vol. I, pp. 540-541).

By such comparisons and inferences, it is concluded that the general conditions of the Proterozoic times were more like, than unlike, those of the present time, though the points of difference were considerable, especially the greater prevalence of igneous action. Both the resemblances and the differences will be more apparent after the details of the formations are studied.

Geographic Relations of the Exposed Proterozoic to the Exposed Archean.

Proterozoic rocks appear at the surface in many parts of North America, but in few regions have they been clearly separated from the Archean, and in very few have their subdivision[illegible] we[illegible]ut so as to permit of their separate delineation on [illegible]s the area where rocks of known Proterozoic ag[illegible]as well as areas where Proterozoic rock[illegible]ave [illegible]ed from the Archean. Where their [illegible] Proterozoic rocks are found to [illegible] in all, with areas of ex[illegible] Archean rocks are associat[illegible] about the borders or a[illegible]s in narrow belts, or [illegible]us relations are sho[illegible] 56.

That the P[illegible]monly about the [illegible]n shows,

in section, the general relations of the Proterozoic s
Archean (Æ) below, and to younger formations (€)

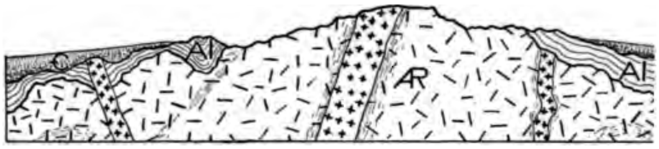

Fig. 51.—Diagram showing a common surface relationship betwee Proterozoic (*Al*), and Cambrian (€). The Proterozoic (Algon appear at the surface between younger and older formations.

same relations are shown in ground-plan in Fig. 52. Whil
shown in these diagrams are common, there are areas

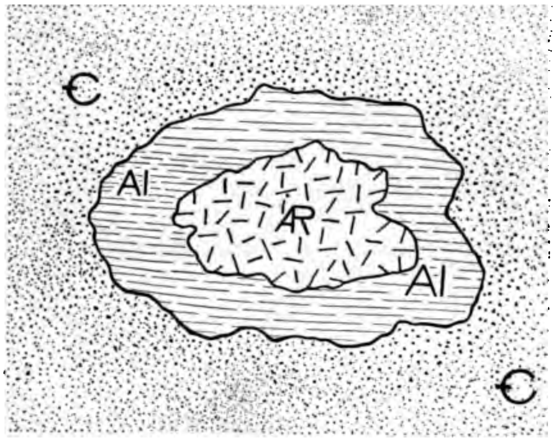

Fig. 52.—Diagrammatic map, showing in ground plan the relat section in Fig. 51.

surrounded or bordered by exposed Proterozoic format
of the latter not associated with exposed Archean. T

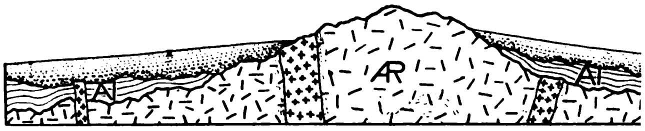

Fig. 53.—Diagram showing how Proterozoic rock (*Al*) may fail Archean (Æ).

tionship is explained by Fig. 53, where a later formatio
as lapping completely over the Proterozoic (*Al*). You

may completely cover the Proterozoic beds on one side of an area of exposed Archean, while they fail to do so on the other (Figs. 54 and 55).

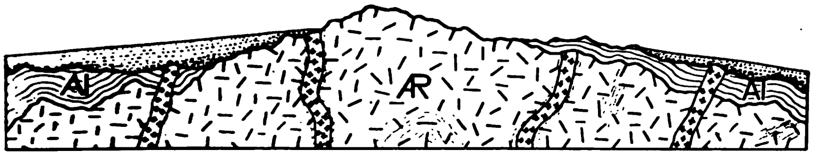

Fig. 54.—Diagram showing how Proterozoic rock (*Al*) may outcrop on one side of an area of Archean (*Æ*) and not on the other.

Belts and patches of Proterozoic rock within areas of Archean (Fig. 56) are often remnants left by erosion, and indicate the former extension of the younger group beyond its present limits.

The occurrence of Proterozoic formations with little surface associa-

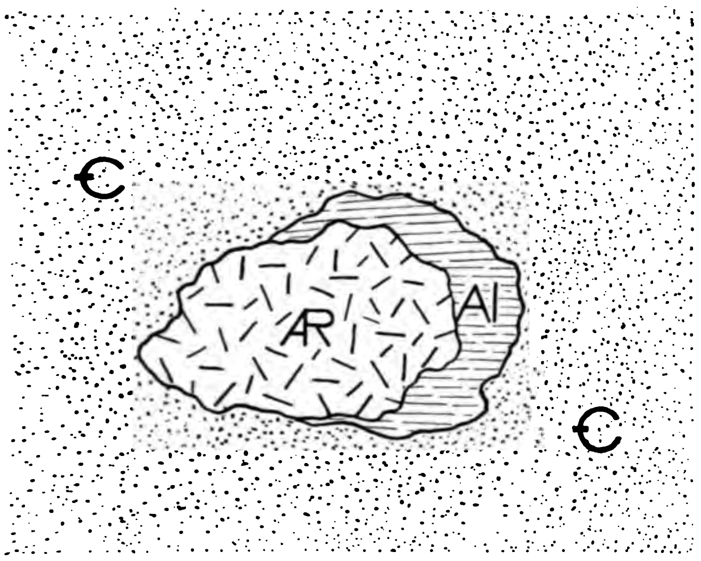

Fig. 55.—Diagram showing in ground plan the relations expressed in section in Fig. 54. *Æ*, Archean; *Al*, Proterozoic; *Ꞓ*, Cambrian.

tion with Archean, is illustrated in the southeastern part of South Dakota and the adjacent parts of Minnesota (Sioux quartzite). The Proterozoic rocks in this region may be presumed to lie on an Archean floor, and an adjacent area of Archean, now mostly covered by younger formations, may be supposed to have furnished the sedi-

ments for the Proterozoic. A sequence of events which v
for the existing relations is illustrated by Figs. 57 and
It is to be borne in mind that the map (Fig. 38) sh
exposed areas (so far as known) of the Archean and Prot

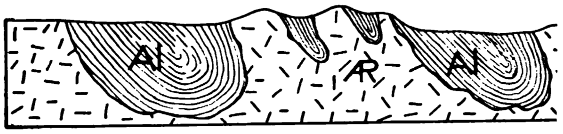

Fig. 56.—Figure showing troughs of Proterozoic rock (*Al*) included i
Marquette region, Mich. Length of section, 2½ miles. (Van H
Smyth, Mono. XXVIII, U. S. Geol. Surv.)

real extent of both systems is much greater. The Prote
Wisconsin are probably continuous beneath younger fo

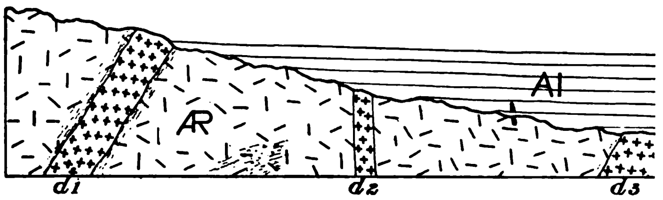

Fig. 57.

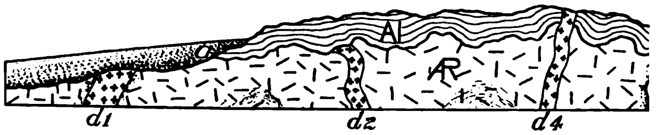

Fig. 58.

Figs. 57 and 58.—Fig. 57 shows Archean rock (*Æ*), on a portion
ozoic sediments (*Al*) have been deposited. Fig. 58 shows the
deformation. The Archean rock (*Æ*) not covered by Proteroz
been depressed and other sediments, *a*, have been deposited upon
that the Archean rock (*Æ*) is nowhere exposed at the surface
rock (*Al*) appears at the surface not in association with outcrops o

the Proterozoic beds of southwestern Minnesota, and
with those of Missouri and Texas (where the pre-Can
probably Proterozoic in part at least) on the south, a
of the Black Hills and Rocky Mountains (where the u
pre-Cambrian of the map, Fig. 38, is at least partly P
the west. The total area where Proterozoic rocks exi

believed to be very great, much greater than the area where they are exposed.

THE PROTEROZOIC OF THE LAKE SUPERIOR REGION.

The Proterozoic formations have been most carefully studied and their relations are best understood in the region about Lake Superior, and the formations of this region have been made the basis for the classification of the Proterozoic group as a whole. The Proterozoic rocks of this region are of great thickness, and, as already indicated (p. 165), they are divisible into at least three great unconformable systems, the relations of which to one another, to the Archean below, and to the Cambrian above, are shown diagrammatically in Fig. 59.

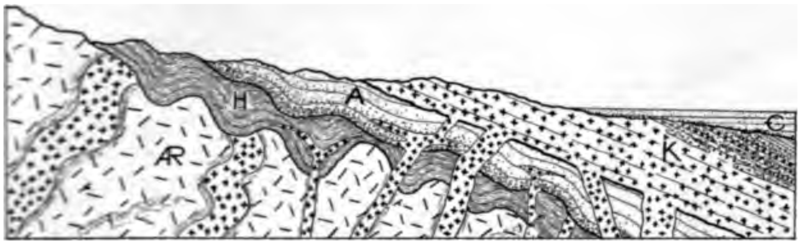

FIG. 59.—Diagram showing the general relations of the three Proterozoic systems of rock in the Lake Superior region. *H*, Huronian; *A*, Animikean; *K*, Keweenawan. The diagram also shows the relation of these Proterozoic systems to the Archean (AR) below and to the Cambrian (Є) above. The cross-pattern represents igneous rock. The lines, dots, etc., above the Archean represent sedimentary beds.

During at least some portion of the Proterozoic era there was probably an island of Archean rock in northern Wisconsin. North of Lake Superior there is a much larger area of Archean rock not known to have been submerged during this period. So far as present knowledge goes, these land-areas may have been sometimes united as a result of the elevation, relative or absolute, of the intervening areas. These land-areas were the chief sources of the Proterozoic sediments deposited in the Lake Superior region.

The Huronian system.

(Lower and Middle Huronian of page 161.)

Composition and thickness.—The rocks of this system are chiefly sedimentary. They include all the common sorts of clastic rocks or

their metamorphosed products, a subordinate amount
and beds of iron ore derived by alteration from beds
(non-clastic) sediments. The beds of limestone (dolc
known to contain fossils, and their organic origin cann
though this is perhaps their most reasonable explanat

The period of Huronian sedimentation was long, for
ably situated thicknesses of sediment to be measured b
feet rather than by denominations of a lower order,
Thicknesses of 6000 feet, and perhaps of 18,000 (see
ported. That sedimentation was not uniform through
is indicated both by the fact that the number of form
in the system is different in different regions, and b
the thickness of a given formation sometimes varies
short distances. In the Menominee region there are f
formations, in the Marquette region nine, while north
thirteen[1] have been enumerated. The lesser number
may be in part the result of erosion which has carried
of the system, but it is also probable that the numbe
did not originally correspond in different parts of the b
consideration.

The sedimentary beds of the Huronian system are c
affected by igneous intrusions of great and small ext
relations of the igneous rocks to the sedimentary,
extrusions of lava and deposits of volcanic clastic
various times during the period, the lavas and tuffs b
turn by sediments. Where the metamorphism has b
not now possible in all cases to say whether a given
rock was intrusive or extrusive, and in many cases
trusive, the date of irruption cannot be fixed. Local

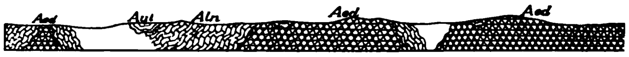

FIG. 60.—Section of the Proterozoic in the Marquette region,
gaunee (iron-bearing) formation (Huronian); *Aui*, Ishpeming
kean); *Aed*, eruptive diabase or diorite. Length of section, 3
Bayley, Smyth, Mono. XXVIII, U. S. Geol. Surv.)

considerable areas, the igneous rocks are more abu
sedimentary in the exposed part of the system (Fig.

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[1] See p. 181, and foot-note 3, p. 151.

Disturbing movements.—After the Huronian formations had attained great thicknesses, the submergence which attended their accumulation was succeeded by a reverse movement, relative or absolute. The beginning of this opposite movement marked the beginning of the end of the Huronian period. The emergence of the land was probably brought about slowly, perhaps as slowly as the submergence which had preceded. Though the border of the sea receded from the position which it had earlier attained, sedimentation continued along its shores at their successive positions. Figs. 61 and 62 will help to make the relations clear. On the supposition that submergence and emergence of the land were gradual, the duration of Huronian sedimentation must have been greater at some points than at others.

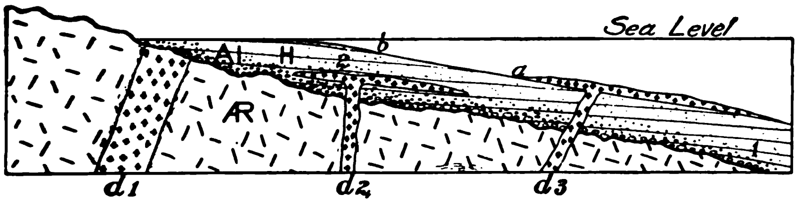

Fig. 61.—Diagrammatic section showing relations which existed around Archean lands during the Huronian period. Huronian sediments (*Al*) are in process of deposition. They are affected by intrusions and extrusions of lava, d_2, d_3, etc.

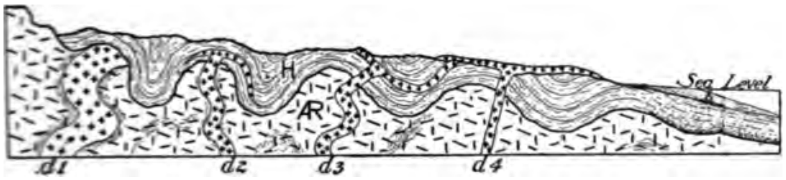

Fig. 62.—Diagram representing the area shown in Fig. 61 after further sedimentation, intrusion, and deformation. Erosion has also affected the deformed beds. It is to be noted that sedimentation is in progress at the right, and that the sediments now depositing, *b*, are conformable on the Huronian sediments, *H*, at the extreme right.

Thus if Huronian sedimentation was brought about by submergence, it began earlier at *a* than at *b* (Fig. 61) and ended later.

Either as the land emerged, or at some time after emergence, the sedimentary beds which had been deposited in horizontal or slightly sloping positions were deformed, being folded in some regions and tilted in others. At the same time it is probable that lava was locally intruded into them and spread out upon their surface. The deformation of the strata and the contemporaneous igneous activity had their effect on the character of the rocks, often rendering them met the metamorphism is, on the whole, most complete wh tion of the beds has been greatest, it is inferred that was a principal factor in the metamorphism. As a re morphic change, slates and schistose rocks of various important components of the system. Fig. 63 represe ral size, the structure of a piece of Huronian rock af

It is not to be understood, however, that dynar agents were the only ones involved in the changes whi

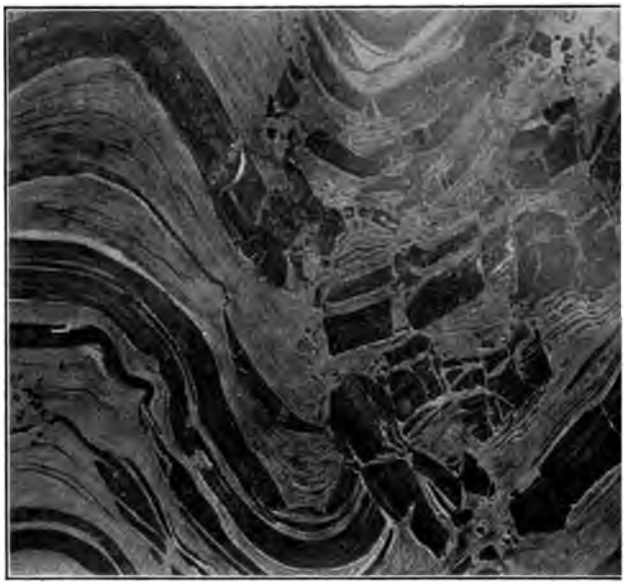

FIG. 63.—Figure showing the deformation of a small piece of H dark bands are jaspilite. The remainder is iron ore (hematite) the bending and breaking shows that the deformation took p combined fracture and flowage. (Van Hise, Bayley, and Smy U. S. Geol. Surv.)

formations have suffered. The sandstones and the quar ates have been transformed into quartzites by other me the iron-bearing formations, originally laid down a ginous carbonates in some cases, and as ferrous-silic ments in others, have been notably changed by pe carrying oxygen, carbonic acid, etc. One of the nge, brought about by dissolving, recombining, and precipitating, the production of beds of iron ore, chiefly hematite.[1]

The sections which follow give some idea of the present conditions the formations.

Sections of the Huronian.—The following Huronian sections, in selected localities where the rocks have been well studied, give some idea of the range of the system.

The Huronian series of *the Marquette region* of northern Michigan[2] rests unconformably on the Archean, and includes, in ascending order, (1) the Mesnard quartzite, with basal conglomerate, and some slate, 110 to 620 feet thick; (2) the Kona dolomite, with some clastic layers, 425 to 1375 feet thick; (3) the Wewe slate, including, besides slate, some conglomerate, quartzite, and schist, 550 to 1050 feet thick; (4) the Ajibik quartzite, which is sometimes schistose, 700 to 900 feet thick; (5) the Siamo slate, with some graywacke and quartzite, 600 to 1300 feet thick; and (6) the highly ferruginous Negaunee formation, which includes sideritic slate, grünerite-magnetite schist, ferruginous chert, jaspilite, and iron ore, and has a thickness of 1000 to 1500 feet.[3] The sideritic slate appears to have been the dominant original type of rock in the Negaunee formation and most of the other phases of this formation have been developed from it. The series also includes some volcanic rocks. The beds are now closely folded and generally much metamorphosed. (Figs. 64 and 65 illustrate the positions of the formations in this region.)

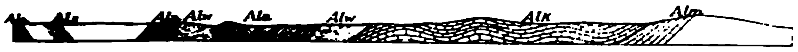

FIG. 64.—Section of Huronian in the Marquette (N. Mich.) region. *Alm*, Mesnard quartzite; *Alk*, Kona dolomite; *Alw*, Wewe slate; *Ala*, Ajibik quartzite; *Als*, Siamo slate. Length of section, 3 miles. (Van Hise, Bayley, and Smyth, U. S. Geol. Surv.)

In *the Menominee* (Michigan and Wisconsin)[4] region, the Huronian system known also as the Lower Menominee) is unconformable on the Archean, and is divided into three formations: (1) the Sturgeon quartzite, with basal conglomerate, 1000 to 1250 feet thick; (2) the Randville dolomite, including some siliceous dolomite, calcareous quartzite, cherty and argillaceous rocks, 1000 to

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[1] For discussion of the iron ores of the Huronian of the Lake Superior region, see Van Hise, 21st Ann. Rept. U. S. Geol. Surv., Pt. III; Irving, Am. Jour. Sci., Vol. XXXII, 1886, p. 255; Van Hise, Vol. XXXVII, 1889, p. 32, and Vol. XLIII, p. 116; and Monographs XIX, XXVIII, XXXVI, and XL, U. S. Geol. Surv.

[2] Van Hise, 15th Ann. Rept. U. S. Geol. Surv., and Van Hise, Bayley, and Smyth, Mono. XXVIII, U. S. Geol. Surv.

[3] According to the classification last suggested (p. 161) the division between the Middle and Lower Huronian is between (3) and (4).

[4] Van Hise and Bayley, Menominee (Mich.) folio, U. S. Geol. Surv.

1500 feet thick; and (3) the Negaunee formation of slight responding with the formation of the same name in the Marq series is closely folded, and the beds are often vertical.

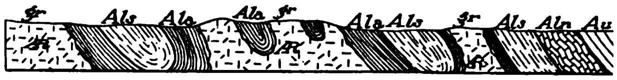

FIG. 65.—Section showing the relations of the Archean, Huronian, one point in the Marquette (N. Mich.) region. *ARgr*, Archean g quartzite), *Als* (Siamo slate), and *Aln* (Negaunee [iron-beari Huronian formations. *Aui* (Ishpeming formation) and *Aum* are Animikean formations. Length of section, 2 miles. (Van Smyth, U. S. Geol. Surv.)

In *the Crystal Falls region* of northern Michigan,[1] the Huro of four formations. In ascending order, these are (1) the Stur the Randville dolomite, (3) the Negaunee formation, and (4) mation. The Sturgeon quartzite has a basal conglomerate ranging from 100 to 1000 feet. It grades into the Randville estimated to have a thickness of 1500 feet. The Negaunee bearing, and is similar to the corresponding formation of the The Hemlock formation consists principally of volcanic rock basic, and of crystalline schists derived from them. The Hur region have been twice folded, the axes of the folds being nea The rocks are notably metamorphosed.

In *the Penokee-Gogebic region* (Wis.-Mich.)[2] two format quartzite (Mesnard) below, and a dolomite (Kona) above. It is the Archean, and has a monoclinal structure, the beds dipping

In *the Mesabi* (*Minn.*)[3] *district*, the Huronian series consists graywackes, slates, conglomerates, and granites, unconformab The thickness is at least 5000 feet, and may be 10,000 feet. schistose cleavage are nearly vertical.

The Huronian of *the Vermilion* (*Minn.*) *region*[4] is made up of members, (1) the Ogishkee conglomerate below, (2) the Ag formation in the middle, and (3) the Knife Lake slates abo conglomerate is a basal conglomerate, unconformable on t Agawa formation has a carbonate, slaty facies, and a chert, and slate facies. Lithologically, it is very like the Soudan forma

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[1] Van Hise, 21st Ann. Rept. U. S. Geol. Surv., and Van His and Bayley, Mono. XXXVI, U. S. Geol. Surv.

[2] Van Hise, 10th and 21st (Pt. III) Ann. Repts. U. S. Geol and Van Hise, Mono. XIX, pp. 127-142, U. S. Geol. Surv.

[3] Leith, Mono. XLIII, U. S. Geol. Surv.

[4] Clements, Mono. XLV, U. S. Geol. Surv.

[5] In the latest publication touching this region, the name of tion is omitted. Jour. of Geol., Vol. XIII, p. 94.

(p. 150). The structure of these formations is so complex, as a result of faulting and folding, that thicknesses are not easily estimated. The thickness of the Knife Lake formation has been estimated at 2500 feet, which is probably less than its original thickness.

In *the area north of Lake Huron*, whence the Huronian system derives its name, the strata formerly included in it consist of great thicknesses of rock, divisible into thirteen formations.[1] Though outside the Lake Superior region, the section is here given. In ascending order the formations are as follows:

(1) Gray quartzite, 500 feet; (2) chlorite slate (altered surface volcanic rock), 3000 feet; (3) white quartzite, 1000 feet; (4) lower slate conglomerate (or graywacke and graywacke conglomerate), 1280 feet; (5) limestone, 300 feet; (6) upper slate conglomerate (or graywacke and graywacke conglomerate), 3000 feet; (7) red quartzite, 2300 feet; (8) red jasper conglomerate, 2150 feet; (9) white quartzite, 2970 feet; (10) yellow cherty limestone, 200 feet; (13) white quartzite, 400 feet; total, 18,000 feet. Some of this is now classed as Animikean.

The first five of the above formations, with an aggregate thickness of about 5000 feet, were formerly regarded as "Lower Huronian"[2] and the others as "Upper Huronian." It is now considered possible that all may be Huronian, as that term is here used.[3] The basal member of this series rests on the Archean unconformably, and there appears to be an unconformity between the fifth and sixth members. The uppermost member is overlain unconformably by Cambrian beds.

It is to be borne in mind that the series of rocks here included under the Huronian have but recently been divided into two systems, and that, if future work shall show that the break between them is important and general, rather than local, one of the divisions will doubtless receive an appropriate name and take its place in the series along with Huronian, Animikean, and Keweenawan.

Erosion of the deformed Huronian system.—The deformation of the Huronian formations at the close of the period brought considerable areas of what had been the sites of sedimentation into positions favorable for erosion. The extent of these areas is unknown, and is likely to remain so, since most of the Huronian strata are now covered by later beds which effectively conceal much of the eroded surface of the Huronian, and prevent the determination of its extent. The period of erosion which followed seems to have been long, but its duration cannot be accurately measured. It is certain that great thicknesses of the sedimentary beds were carried away, for the stubs of great folds,

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[1] Logan, Rept. of Progress of the Geol. Surv. of Canada, 1863. Van Hise, 16th Ann. Rept., Pt. I, U. S. Geol. Surv., p. 776.

[2] Van Hise, Bull. 86, U. S. Geol. Surv. See also Jour. of Geol., Vol. XIII, p. 98.

[3] Coleman, American Geologist, Vol. XXIX, 1902, pp. 327–334. Willmott, Am. Geol., Vol. XXVIII, pp. 14–19, thinks most of this Huronian equivalent to the "Upper" Huronian of Canadian geologists.

truncated before the deposition of the next succeeding
that thousands of feet of sedimentary rock must have
from their crests. Such remnants of this formation as es
tion are in some places known to possess a thickness
feet (Marquette district of northern Michigan), and if a
Huronian of the area north of Lake Huron be Huroni
meaning of the term as here used, the thickness is 18,0
other places the Huronian strata were completely rem
with an unknown thickness of the Archean below.
such data as are at command touching this question, it
improbable that the erosion interval which followed th
Huronian beds was as protracted as the interval duri
accumulated.

The erosion of a land surface implies sedimentation
ders. The materials worn from the Archean and Huro
during this period of erosion were probably carried to
main, and deposited chiefly near its shores; but where t
during this time there are no means of knowing, since th
made seem to have been covered, in large measure, by l
and not since exposed.

Contemporaneous events elsewhere.—The process
going on about Lake Superior were doubtless in operati
other land-mass of the time; but it does not necessa
the areas of sedimentation were extended and contr
regions just as they were about Lake Superior. It is a
ally observed in geological nomenclature that the nar
series or a formation in one place is not given to a series
in another, unless there is strong reason for believing the t
contemporaneous, or essentially contemporaneous, in
therefore, there are rocks in other localities which doubt
in age with the Huronian of Lake Superior, their contempo
been proved, and the term Huronian is not generally ap

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[1] Ante, p. 151.

[2] For a fuller description of the "Lower" Huronian of the La
and of the early Algonkian of other regions, see Van Hise, Bull. 8
Monos. XIX, XXVIII, XLIII, and XL, and the 21st Ann. Rept., Pt. I
For a discussion of the principles involved in the study of comple
fossiliferous rocks, such as the Archean and Algonkian of Lake Su
tion, Irving, 7th Ann. Rept., U. S. Geol. Surv.

The Animikean system.

(The Upper Huronian of some authors.)

General relations.—After erosion had long operated on the deformed Huronian rocks, much of the area about Lake Superior again became the site of deposition. The change was probably brought about by slow subsidence, and as it progressed, the sea appears to have encroached upon the areas which, while land, had suffered extensive erosion. Meanwhile great areas of the earth's surface probably remained continuously under water, and were the sites of deposition. Sedimentation was renewed in the Lake Superior region, probably under conditions similar to those which existed at the beginning of the Huronian period. With the renewal of sedimentation, there was begun a second series of sedimentary beds lying on the eroded surface of the first.

While the Animikean series is, as a rule, unconformable on the Huronian where their contact is seen, it does not follow that this is their universal relationship. Wherever the Huronian formations were not exposed to erosion before the deposition of the next succeeding series, their relation to the Animikean must be one of conformity. The area of conformity, the whole earth considered, must be far greater than the area of unconformity, though the latter is the rule where the contact of the two systems is known. In some parts of the Lake Superior region the subsidence of the Animikean period appears to have been so great that the sea covered the whole of the Huronian series, and reached the Archean beyond. In such places Animikean sediments were deposited on the Archean.

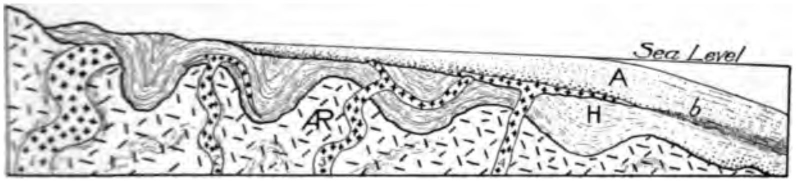

FIG 66.—Diagram showing same area as Fig. 62, after subsidence, which allows of sedimentation over a part of the eroded surface of *H*. At the right the sediments *b* are conformable on *H*; at the left, sediments *A* are unconformable on *H*.

Composition.—The source of material of the Animikean system is readily understood. All the exposed Archean and all the exposed Huronian formations probably made their contributions. Sediments

precipitated from solution also seem to have entered int
as in the case of the iron-bearing formations. The ch
beds as first laid down was much the same as that of
The fact that the succession of clastic formations is no
different parts of the region shows that the conditions of
varied from point to point about the ancient lands, ev
Lake Superior region.

Certain characteristics of some of the rocks of this s
special mention. Within the system there are consi
nesses of black shale, the color of which is due to the pres
often in considerable quantity. Where the rocks are hi
phic, the black shale has been changed to graphitic sch
tent of carbon is thought to imply the existence of l
fossils have been found in the Lake Superior region.

Another peculiar and important part of the syste
ore. Here belong the iron ores of the Mesabi (Minn.),
bic (Wis. and Mich.), and Menominee (chiefly Mich.)
the Archean and Huronian, the ore is in the form of ferri
hematite, Fe_2O_3), but, as in those systems, the ferrugin
originally consisted of iron-bearing cherty carbonates,
containing ferrous silicate. In so far as the iron wa
both its original form and the changes through whic
seem to imply the existence of life during the period

Igneous rocks.—There is reason to believe that igne
active during the period, and that lavas were sometim
the beds, and into the Archean and Huronian bene
amount of igneous rock associated with the system is g
predominating (as at the east end of the Penokee-Gogeb
over the rocks of sedimentary origin.

Thickness of sediments and duration of the period.-
Animikean sedimentation continued until sediments m
of feet in thickness had accumulated. In the Penol
portion of the system which still remains after notab
erosion, has an estimated thickness of about 14,000
regions the thickness of what now remains is 500
though the average, where definitely known, is consid
is certain, however, that existing thicknesses often fall
original, for the portions now remaining sometimes (M

show that they were deformed and metamorphosed when they lay far (probably many thousand feet) below the surface. It is impossible to estimate in years, even approximately, the duration of the period, but it may well have been as great as that of the Huronian.

Deformation and erosion.—After the Animikean formations had attained great thicknesses, the bed on which they rested suffered widespread, but not universal, deformation, and as the sea receded from its former shores it exposed a surface covered by the new formations. So soon as they emerged from the sea, they were subject to erosion (Fig. 67).

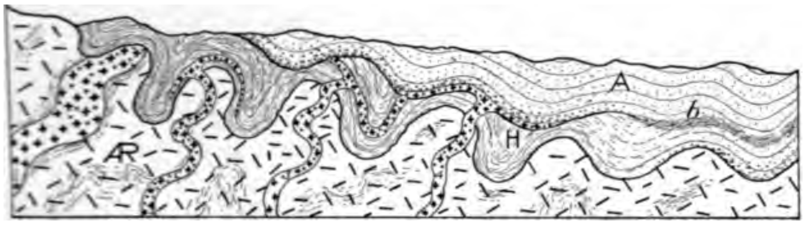

Fig. 67.—Diagram showing same area as Fig. 66 after the Animikean beds, *A*, have been deformed and eroded.

The sediments worn from them were carried down to lower levels and deposited; but the sites of deposition during the early part of this erosion interval have not been seen, or, if seen, have not been recognized. The deformation which inaugurated the period of erosion was probably slow, and the area converted into land seems to have remained above the water for a period of time long enough to allow of extensive erosion. Its amount cannot now be accurately measured, but it is certain that thousands of feet of rock were removed from the surface of the Animikean system in many places.

Alteration of the rocks.—In general the rocks of this system have been less metamorphosed than those of the preceding. This fact, as well as the attitude of the strata, indicates that they have been subject to less dynamic action. In some regions, as on the north shore of Lake Superior, the strata are still approximately horizontal; in others, as on the south shore of Lake Superior, they are notably deformed (Figs. 68 and 69). The forces involved in the transformation of the Animikean beds affected the Huronian systems at the same time, and the metamorphism of the latter may be in part the result of changes effected during the deformation of the former. But while the Amini-

kean beds are still shales, sandstones, and conglomerates i
profound changes during the deformation which followe

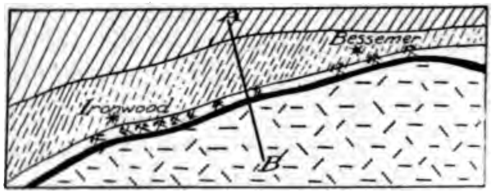

FIG. 68.

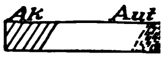

FIG.

FIG. 68.—Map of a small area in the Penokee-Gogebic region of Nortl region of important iron mines.

FIG. 69.—Section along the line *Ab* of Fig. 68. Shows the relation o beds to the Archean in the Penokee-Gogebic region. *Æ*, Archea (Palms formation), *Aui* (Ironwood formation [iron-bearing]), and *A* are Animikean formations. *Ak*, Keweenawan formation. Lengt miles. (Van Hise, 21st Ann. Rept., Pt. III, U. S. Geol. Surv.)

sition, or subsequent to it, have affected them in othe
these common sorts of sedimentary rock into slates, schis

Distribution.—The Animikean rocks are most com
at the surface either about the borders of the Archean or t
though isolated areas of them, not in surface associatic
formations, are known at a few points (south-central Wis
western Minnesota, and southeastern South Dakota, et
Their exposed parts do not, as a rule, constitute large ar
real extent beneath other formations is doubtless great.
extent was as great as that of the areas of sedimentatio
Animikean period, and their present extent must be the s
area whence they have been removed by erosion.

The following sections of the Animikean in selected lo
the series has been studied in detail, give some idea of i

Sections of the Animikean.—In *the Marquette*[1] *region*, the Ani
Marquette series) is unconformable on the Archean and Hu
divided into three formations: (1) the Ishpeming at the base,
gamme, and (3) the Clarksburg. The Ishpeming formation is ch
with a basal conglomerate, but it also includes banded mag
schist. Its thickness is 1550 feet and less. The Michigamme

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[1] Van Hise, 15th Ann. Rept., U. S. Geol. Surv., and Van Hise, Ba
Mono. XXVIII, U. S. Geol. Surv.

originally composed of ferruginous and non-ferruginous muds and grits, now altered into slates, graywackes, schists, and gneisses. The predominant rocks of the Clarksburg formation were volcanic flows, tuffs, ashes, and breccias, now represented by greenstones. Interbedded with the greenstones are some graywacke, conglomerate, slate, etc. The formation does not lie above the Michigamme formation in stratigraphic sequence. It grades below into the Ishpeming formation at some points, and into the Michigamme at others; while above, it sometimes grades into the latter. In origin, therefore, it was contemporaneous with parts of the Michigamme formation. The aggregate thickness of the Upper Marquette series is not accurately known, but is probably more than 5000 feet, and perhaps as much as 10,000 feet. Figs. 70–72 show the relations of these to older formations.

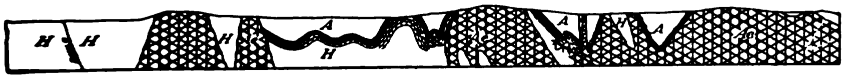

Fig. 70.—Section showing the relations of Huronian and Animikean, in a portion of the Marquette (N Mich.) region, where eruptive rocks exceed the sedimentaries. *H*, Huronian; *A*, Animikean; *Ae*, eruptive diabase. Length of section, 3 miles. (Van Hise, Bayley, Smyth, U. S. Geol. Surv.)

The deformation and metamorphism of the Animikean rocks of this region at the close of this period was great. They now occur in a great east-west synclinorium, and the alterations of the rocks were such as to show that the beds now accessible were in the zone of combined flowage and fracture, and therefore far below the surface, when they were deformed and metamorphosed. In spite of the great changes which these beds have suffered, they are less metamorphic than those of the Huronian system (Lower Marquette) of the same region.

In *the Menominee region*,[1] the *Animikean* (or Upper Menominee) series includes (1) the Vulcan formation and (2) the Hanbury slate. The former, with a ferruginous basal conglomerate, rests unconformably on older rocks, and is made up of quartzites, ferruginous quartzose slates, jaspilites, and iron ores. It has a thickness of 600 to 700 feet. The Hanbury formation is primarily slaty, but includes some iron ore and ferruginous chert, and has a thickness of perhaps 2000 to 3000 feet. The series is closely folded and much metamorphosed. The distinction between it and the Huronian is much less than in the Marquette region. They are separated mainly because of the basal conglomerate at the bottom of the series.

The Animikean system is represented in *the Crystal Falls district* of Michigan [2] by the Michigamme formation, unconformable on the Huronian. Slates, mica schists, ferruginous cherts, actinolite and grünerite schists, an included in the formation. The sedimentary beds are affected rocks of which range from acid to ultra-basic. The thickness of is about 2000 feet.

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[1] Van Hise and Bayley, Menominee folio, U. S. Geol. Surv.

[2] Van Hise, 21st Ann. Rept., U. S. Geol. Surv.; and Van Hise, and Clements, Smyth, and Bayley, Mono. XXXVI, U. S. Geol. Surv.

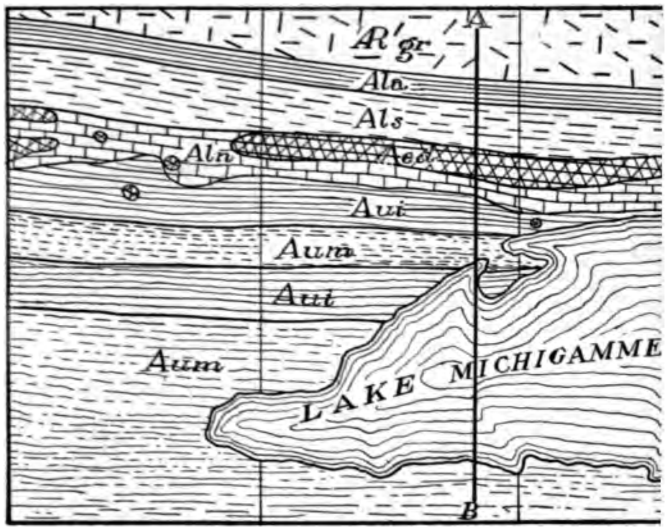

FIG. 71.—Map showing the surface relations of Archean, Huronian, formations in a small area in northern Michigan. *ÆRgr*, Arche (Ajibik quartzite), *Als* (Siamo slate), and *Aln* (Negaunee [iron-bearin Huronian formations. *Aui* (Ishpeming formation) and *Aum* (Mic tion) are Animikean formations. *Aed*, eruptive diabase or dio area, 3 miles. (Van Hise, Bayley, and Smyth, U. S. Geol. Surv.

In *the Penokee-Gogebic region* of Wisconsin and Michigan,[1] consists of (1) the Palms formation below, a quartz slate formal conglomerate, resting unconformably on the Huronian or the having a thickness of 300–800 feet; (2) the Ironwood formatio (*a*) cherty iron carbonate, (*b*) ferruginous slates and cherts, an and magnetitic slates. The cherty iron carbonate represents tl

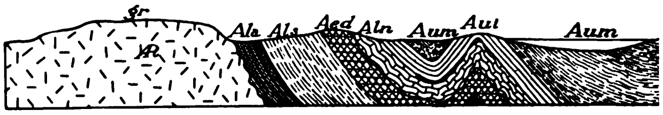

FIG. 72.—Section along the line *Ab* of Fig. 71.

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[1] Van Hise, 10th and 21st Ann. Repts., U. S. Geol. Surv.; Irvin Mono. XIX, U. S. Geol. Surv.

dition of the formation, the others being secondary phases. Iron ore (iron oxide) is found in the lower part of the formation, usually just above the Palms formation. The Ironwood formation has a thickness of about 850 feet. The uppermost formation of the series is (3) the Tyler slate, locally altered to schists The thickness of this formation exceeds 12,000 feet. The structure of the Animikean of this region is monoclinal (dip of 60° to 70°), but a series of transverse folds has been superposed on the monoclinal structure.

In *the Mesabi region*,[1] the Animikean includes three formations. In ascending order these are (1) the Pokegama quartzite, with basal conglomerate, resting unconformably on Archean and Huronian, 0–500 feet thick; (2) the Biwabik (iron-bearing) formation, consisting of cherts, with ferruginous slates, quartzites, and iron ores (iron oxides). The formation from which these varieties of rock were derived consisted largely of granules of green ferrous silicate, to which the name *Greenalite* has been given. The thickness of the Biwabik formation may range from 200 to 2000 feet. Locally it is profoundly metamorphosed by contact with the gabbro and granite of the Keweenawan series. Above the Biwabik

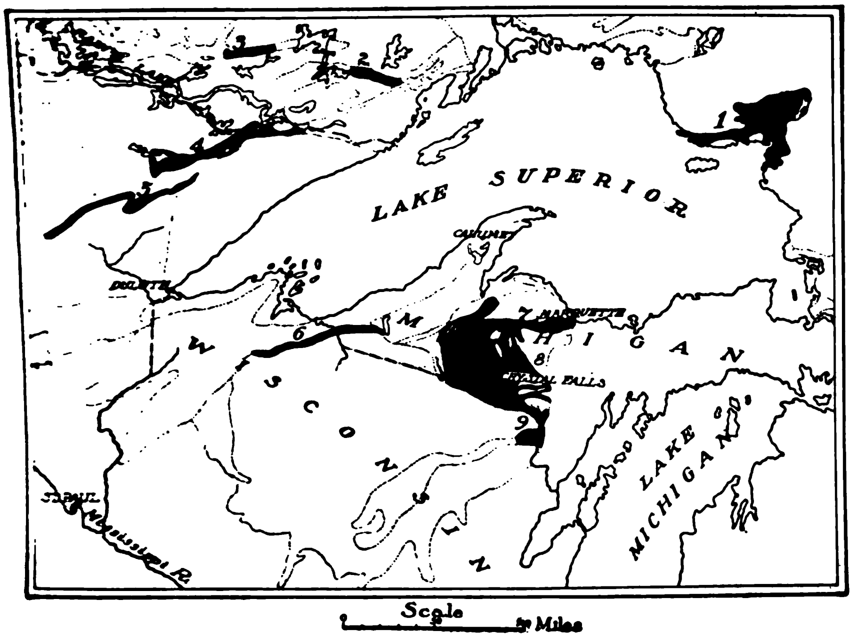

FIG. 72a.—Map showing (in black) the position of the iron-producing areas in the Lake Superior region. 1, Michipicoten district; 2, Kamanistquia and Matawin district; 3, Steep Rock Lake and Attikokan district; 4, Vermilion district; 5, Mesabi district; 6, Penokee—Gogebic district; 7, 8, and 9, Marquette, Crystal Falls, and Menominee districts.

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[1] Leith, Mono. XLIII, U. S. Geol. Surv.

formation is (3) the Virginia slate, which includes, besides sla wacke, and some limestone. Its thickness has not been determ Biwabik formation, it is locally metamorphosed by igneous c beds dip south and southeast at angles of 5° to 20°. The d gently cross folded, the axes of the folds pitching south. Th of the series with older rocks is shown by (1) basal conglomer ance of dip, (3) differences in amount of deformation and metam tribution, and (5) relations to intrusive rocks.

In *the Vermilion region*,[1] the *Animikean* series consists of tw able members, the Gunflint formation below, and the Rove above. The former (= the Biwabik of the Mesabi region) is and granular quartzose bands with more or less carbonate, band netic chert, and quartz with crystals of actinolite, grünerite, et more or less iron carbonate, magnetite, hematite, and limonite (r valuable). The formation has been estimated to be something thickness. The Rove slate formation (probably = the Virginia f Mesabi region) has, in addition to the slate, some graywacke and and is locally metamorphosed by igneous content. The syste some igneous rock. Its thickness is undetermined. The structu is rather simple, being largely monoc.inal.

Iron ore in the Lake Superior region.

Production.—The region about Lake Superior yields than any other area of equal size in the world. The of the region has nearly trebled in ten years. In 1902, production of ore from that part of this region which l United States was 26,977,404 long tons.[2] This is abou of all that was produced in the United States that ye Mesabi region produced nearly one-half. In 1900, the last statistics for other countries are available, the iron ore p Lake Superior region of the United States was about the total production for that year.

Geologic positions.—The ores of this region are partly i as in the Vermilion region of Minnesota, partly in the in the Marquette region of Michigan, but most largely in t as in the Menominee and Gogebic regions of Michigan a in the Mesabi region of Minnesota, and some of those in region. The following table gives the production in tons f regions for the ten years preceding 1902:

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[1] Clements, Mono. XLV, U. S. Geol. Surv.

[2] Mineral Resources of the United States for 1902.

	1892	1893	1894	1895	1896
Vermilion..........	1,226,220	815,735	1,055,229	1,027,103	1,200,907
Marquette.........	2,848,552	2,064,827	1,935,379	1,982,080	2,418,846
Menominee........	2,402,195	1,563,049	1,255,255	1,794,970	1,763,235
Gogebic...........	3,058,176	1,466,815	1,523,451	2,625,475	2,100,398
Mesabi............	29,245	684,194	1,913,234	2,839,350	3,082,973
Total........	9,564,388	6,594,620	7,682,548	10,268,978	10,566,359

	1897	1898	1899	1900	1901
Vermilion.........	1,381,278	1,125,538	1,643,984	1,675,949	1,805,996
Marquette.........	2,673,785	2,987,930	3,634,596	3,945,068	3,597,089
Menominee........	1,767,220	2,275,664	3,281,422	3,680,738	3,679,408
Gogebic...........	2,163,088	2,552,205	2,725,648	3,104,033	3,041,869
Mesabi...........	4,220,151	4,837,971	6,517,305	8,158,450	9,303,541
Total.........	12,205,522	13,779,308	17,802,955	20,564,238	21,445,903

Reference has already been made on preceding pages (p. 150 and p. 176) to the origin of the ores, and to the literature (p. 179) bearing on the subject. Figs. 73 and 74 illustrate on a large scale the association of iron ore and jaspilite in the Marquette region, and at the same

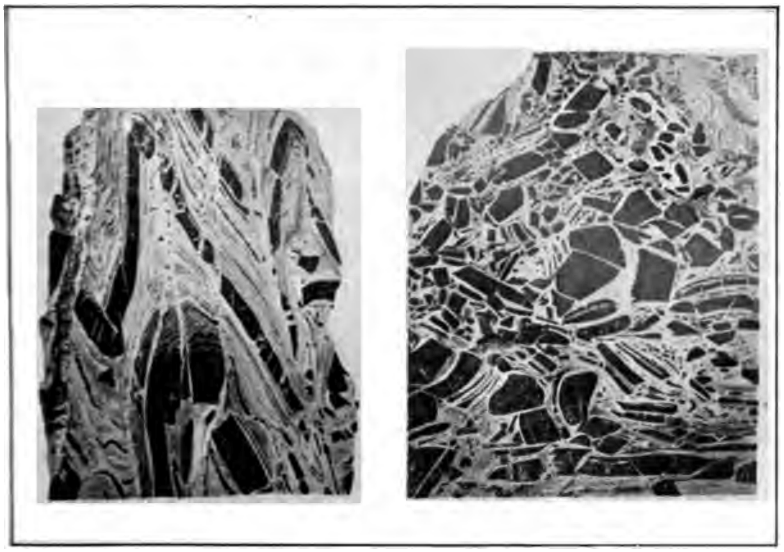

FIG 73. FIG. 74.

FIGS 73 and 74.—Figures showing deformation and disruption as illustrated by specimens of jaspilite ore from Jasper Bluff, Ishpeming, Mich. (Van Hise, Bayley, and Smyth, Mono. XXVIII, U. S. Geol. Surv.)

time give some idea of the deformation and disruptior Huronian rocks have been subject.

The Keweenawan system.

Constitution and thickness.—Overlying the Animike conformably, there is, in some parts of the Lake Sup third series of pre-Cambrian rocks, the Keweenawar Keweenaw Point (N. Mich.) is shown in Fig. 75, and a Keweenawan system in Fig. 76. The maximum thicknes has been estimated at nearly 50,000 feet, but it is not i this estimate is an exaggerated one. If it be correct, th is the thickest body of post-Archean rock referred to a This seemingly incredible thickness may merely mean sition, with subsequent tilting and shearing, as explai and the estimate be altogether correct.

The lower and thicker portion of the system is mad igneous rock, representing a succession of lava flows while the upper part is chiefly sedimentary. The earli seem to have occurred on the land, and to have succeed at short intervals, for the surface of one flow was not se by surface agencies before the next overspread it. In p aceous surface of a flow is still preserved beneath that n and serves to distinguish one lava flow from another. period, the intervals between the flows of lava appear t longer, and thin beds of sediment were deposited bet sheets of igneous rock. Still higher in the series, t beds increase in importance, while the thickness of t lava beds becomes less, until, in the upper part of t lava beds fail altogether, and there follows a successio and conglomerates having an estimated maximum thi thing like 15,000 feet.

The igneous rocks of the system consist principally bases, and porphyries, but other varieties are also presen is greater in the upper part of the igneous division thar

The sedimentary rocks associated with the igneous

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[1] A general account of this series is given in Vol. I, Geology see also other Wisconsin and Michigan reports, and Mono. V, U.

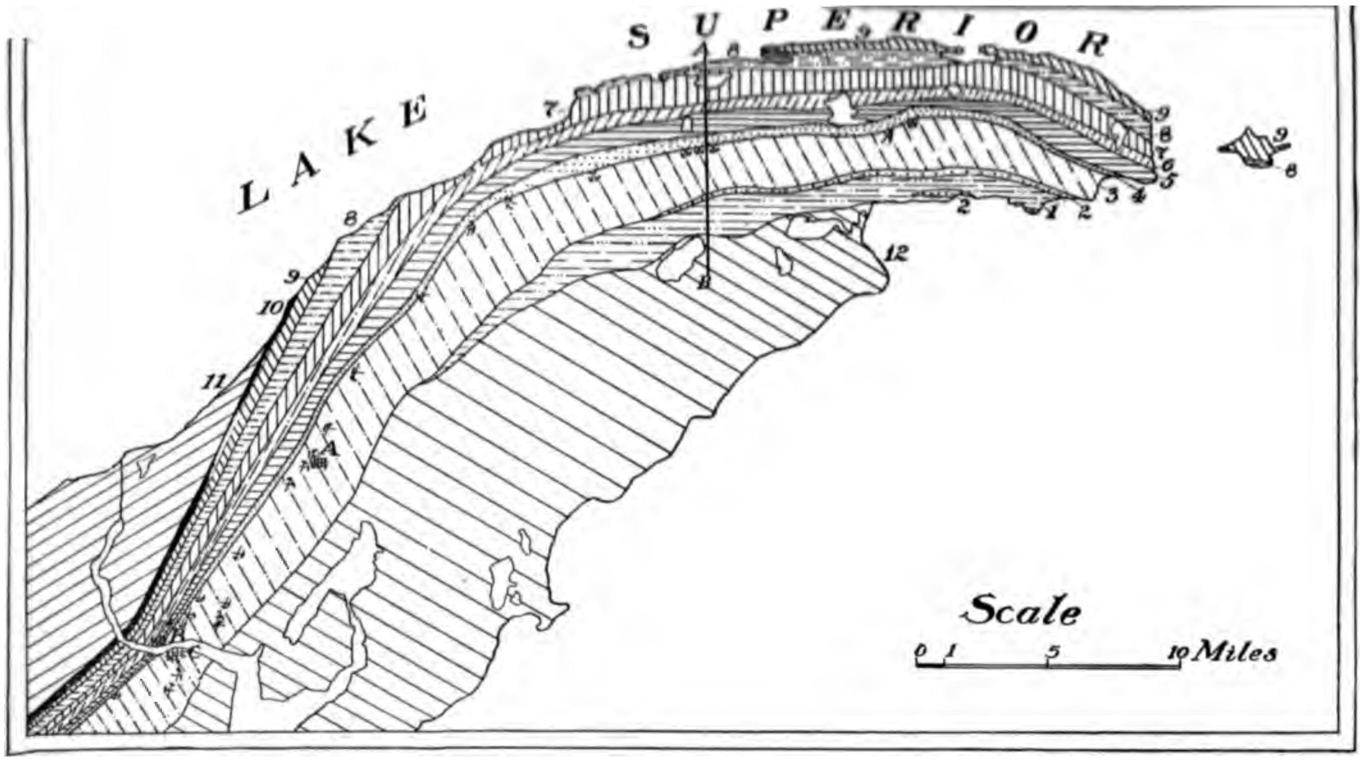

FIG. 75.—Map showing the geology of Keweenaw peninsula (N. Mich.). (1) Diabase and other sorts of igneous rock, including some conglomerate beds; (2) quartz-porphyry and felsite; (3) diabase, melaphyrs, etc., including some conglomerate beds; (4) melaphyrs, gabbros, etc.; (5) diabase, etc., with some conglomerate beds; (6) diabase, etc., with sandstone beds; (7) red sandstone and conglomerate; (8) diabase and some conglomerate; (9) red sandstone and conglomerate; (10) black shale and gray sandstone; (11) red sandstone; (12) Potsdam sandstone. All but the last are Keweenawan. (Irving, Mono. V, U. S. Geol. Surv.)

them were largely derived from the igneous rock itself.
is such as to indicate that they accumulated rapidly.
enormous thickness, therefore, it is not clear that this
occupied more time in its formation than either of t
preceded, and perhaps not as much.

In the valley of the St. Croix river, in northwestern
the adjacent parts of Minnesota, there are said to be 65
5 conglomerate beds in succession, with neither top nor b
The aggregate thickness of the exposed part of the
locality has been estimated at 20,000 feet.

Some of the igneous rocks, such as the gabbros of
and Mesabi[3] regions, are intrusive (laccolithic), whi
the St. Croix valley, represent fissure eruptions. The
bros and granites of the Mesabi region have occasioned
morphism in the rocks into which they were intruded
(Duluth) of the Vermilion region contain masses of ti
netite, believed to have arisen from segregation in the
The magnetite is not of commercial value. Dikes and
of acid igneous rocks affect the more basic portions, an
occurrence.

Deformative movements.—The sedimentary part of
wan series has usually been thought to imply mari
but the sediments may have been accumulated in an i
may be more or less subaërial. If they are marine, t
ness and their derivation mainly from the lavas of
seem to imply crustal warping throughout the peri
erosion fields and furnish the necessary sites for the
they are merely lodgment deposits on the low lava slo
little movement need be assumed during their dep
subsequent deformation need only have been simpl
mild, while the thickness is not incredible (see p. 260
view it was probably during and at the close of this
Lake Superior syncline (Fig. 77) was formed, in pa
the Keweenawan rocks tilted toward its axis, both
and south. It is not to be understood that this syncl

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[1] Hall, Bull. Geol. Soc. Am., Vol. XII, pp. 313–

[2] Clements, Mono. XLV, U. S. Geol. Surv.

[3] Leith, Mono. XLIII, U. S. Geol. Surv.

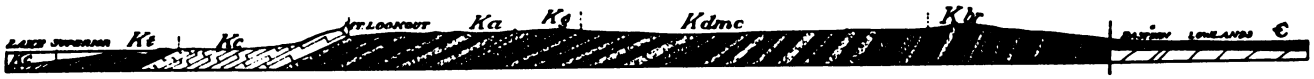

FIG. 76.—Section across the Keweenawan peninsula, along the line *AB* of Fig. 75. *Kbr*, Bohemian Range group; *Kdmc*, diabase, melaphyr, and conglomerate; *Kg*, greenstone group; *Ka*, Ash-bed group; *Kc*, Great conglomerate; *Kt*, Lake Shore trap; *Kc*, Outer conglomerate.

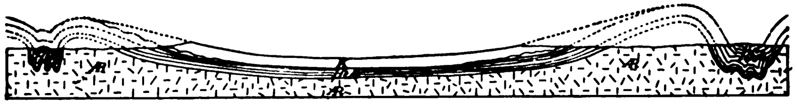

FIG. 77.—Diagram illustrating the development of the Lake Superior syncline. Æ, Archean; *H* and *A*, Huronian and Animikean; *K*, Keweenawan. (Irving, Mono. V, U. S. Geol. Surv.)

a surface depression since this time. On the contrary sequently filled with sedimentary beds, and the depres by the present lake is the result of subsequent excavat relatively recent origin. The deep bowing of the serie part, the distribution of the exposed portions of the system, which comes to the surface chiefly about the syncline (Fig. 77). As originally laid down, the system of covering all of the Animikean, and its distribution, c that of the preceding systems, seems to indicate that t of the northern interior were more extensive in the Kewe than during either of the periods preceding.

After the accumulation of the enormous thicknesses o sediments, the region about Lake Superior suffered defor ently in common with other parts of the continent, an regarded as marking the end, or the beginning of the e terozoic era in this region.

As a result of the deformation at the close of the some parts of the area where Keweenawan sediments had were brought into such an attitude as to be subject to e change did not cause great deformation of the strata. ally tilted, and locally, folded and faulted as well (Fig though this is not the rule. In keeping with their struc are not metamorphic. The sandstones, graywackes, and are sandstones, graywackes, and conglomerates still. rock of the series likewise remains, for the most part, state, not having been made schistose after the fashion rocks intruded into the Huronian, and to a lesser e Animikean system.

After the warping which followed the deposition nawan formation, the exposed surfaces of Keweenaw Huronian, and Archean rocks suffered protracted erosi the land about Lake Superior again sank, and when back, a new series of sedimentary beds was deposite bly on the eroded surface of those which had preced sea came back, its waters teemed with life, for the deposited contains abundant fossils. This abundant formation, resting unconformably on those which ha classed with the Cambrian system, the oldest system c

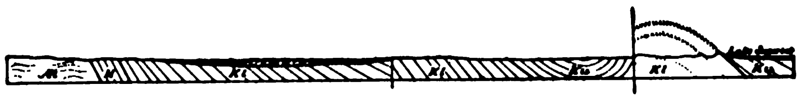

FIG. 78. Section illustrating the deformation of the Keweenawan beds. *Æ*, Archean; *H*, Earlier Proterozoic; *Kl*, Lower Keweenawan; *Ku*, Upper Keweenawan; *€*, Cambrian. Diagram shows faulting and folding. Length of section, 44 miles. (Irving, U. S. Geol. Surv.)

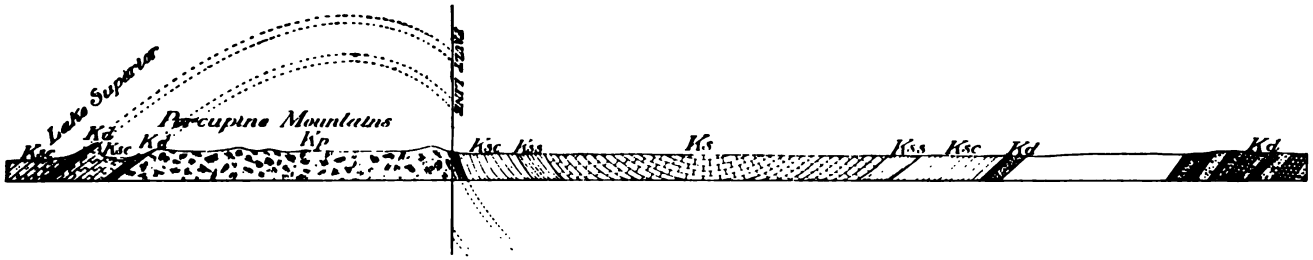

FIG. 79.—Diagram illustrating the deformation of Keweenawan beds in the vicinity of Porcupine Mountain, N. Mich. *Kd*, diabase; *Kp*, porphyry; *Ks*, sandstone; *Ksc*, sandstone, conglomerate; *Kss*, sandstone, shale. Length of section, 15 miles. (Irving, U. S. Geol. Surv.)

era. It is because of the difference in the rocks, fauna below and above the post-Keweenawan-pre-Cambrian as much as because of the greatness of the physical cha it, that the close of the Keweenawan is taken to mark era, rather than simply the end of a period.

Copper.—The Keweenawan system contains the n deposits of native copper known. The metal occurs in cracks of the igneous rock, but more abundantly in between the pebbles and grains of some parts of the sed In the conglomerate at some of the richer mines, the cop dant as to be one of the important cementing materia In its present form, it is believed to be a precipitate solution, and to have been concentrated in its preser ground water. The original source of the metal was igneous rock itself. The date of concentration is un

In 1875 the Keweenawan formation of northern Mi 16,089 tons of copper, or about 90 per cent. of all that in the United States. In 1901, the same area yielde This was about 26 per cent. of the copper produced i that year.[2]

General Considerations Concerning the Lake Proterozoic.

Duration of time.—It is difficult adequately to c enormous lapse of time involved in the accumulation thicknesses of rock as have been referred to in the prece none of the estimates are exaggerated, there is an agg than 30,000 feet of sedimentary rocks in the Prote The accumulation of such thicknesses of sediment woul a vast lapse of time, and when it is remembered that th are separated from one another by unconformities, may represent a time interval as long as that involved i tion of a system, and that at least some part of the tim the unconformities below the Huronian and above th were developed is to be assigned to the Proterozoic, it

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[1] For discussions concerning the copper, see Pumpelly, Geol. Su 1869-73, pp. 19-46; Irving and Van Hise, Mono. V, U. S. Geol. Sur Vol. I, Geology of Wisconsin.

[2] Mineral Statistics for 1902, U. S. Geol. Surv.

seen that the duration of the Proterozoic era was exceedingly great. If length of time may be estimated from thicknesses of sedimentary beds, the duration of the era is comparable to all succeeding time.[1] It is at present impossible to state the length of geological periods in numerical terms, but it would appear that the duration of the Proterozoic era should be spoken of in terms of millions or tens of millions of years, rather than in terms of a lesser denomination.

The sources of the sediments.—It should also be noted that these extraordinarily thick beds of sediment mean the destruction of a still larger amount of some older rock. The volume of rock destroyed must have exceeded the fragmental product deposited by the amount of mineral matter which remained in solution in the sea at the close of the period, together with such amount as had been carried down by ground water to levels below the surface, and there deposited.

It is important to note further that a large portion of the sediments was produced by *mature decomposition* of older rocks, and this implies that they were not derived by rapid mechanical abrasion such as that which accompanies and follows great elevation and excessive precipitation. The great series of quartzites were derived from the complete decomposition of quartz-bearing rocks, and involved the almost complete separation of the quartz grains from other constituents, while the thick beds of shale arose from the complementary clayey products of decomposition, from which most of the basic oxides had been removed by carbonation. It is scarcely too much to say that the materials of the larger part of these great series first became soils on the surface of the parent areas, and were only removed at a rate that permitted the renewal of the soil beneath as fast as it was washed away above. This mode of derivation is perhaps the most important distinction between the Proterozoic series, as a whole, and the Archean.

The sediments involved in the Huronian formations were derived from the Archean; those involved in the Animikean, from the Archean and Huronian. It follows that the Animikean system had its ultimate origin in the Archean, except in so far as it was derived from igneous rock intruded into the Huronian during or after the formation of that system. If the Archean lands in the vicinity of Lake Superior were high enough at any one time to give origin to the thick sediments involved in the Huronian and Animikean systems, their perhaps have surpassed any elevation now existing on the earth. It is not probable, however, that such enorm existed at any time. It is more probable that as erosi the land itself reacted by rising slowly, or that further place, or that the sea bottom sank, drawing off the wate the land *relatively* higher. In this way, degradation may have been in progress at the same time, and the on never have got far ahead of the other. It is even belie geologists that the removal of sediments in large quant land would allow it to rise, and that their deposition on tom would cause that to sink. This doctrine is know

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[1] Van Hise, Bull. 86, U. S. Geol. Surv., p. 491.

Succession of events.—Reviewing the succession of Lake Superior region, we find (1) that the land was high the Archean rocks came into position for its surface to and that the period of erosion was long, but that the sites sedimentation are unknown. (2) The Archean land was so eroded or deformed as to permit the deposition Huronian (p. 161) sediments on portions of its eroded The area of the former Archean land, together with the L beds about it, was again brought into such an attitud by crustal warping, that it was subject to a long period o contemporaneous sedimentation elsewhere. During the deformation, the rocks involved were metamorphosed. land seems to have sunk, allowing the sea (or at any r for deposition) to cover a large part of the territory w above sea level, and to deposit upon its eroded surface th the Middle Huronian system. (5) After this period of the land seems to have emerged, exposing the landw the Middle Huronian system, and all the older rocks not to erosion. (6) Submergence of the eroded surface o Huronian was followed by the deposition of the Anim (7) This newly deposited system then emerged over gr was exposed to erosion. This emergence was accompa deformation and metamorphism. At various stages in of these changes there were intrusions and extrusions of a scale that the aggregate amount of igneous rock a the sedimentary is very great. The igneous activity

netamorphism of the sedimentary portions of the Huronian and
ikean systems. (8) After erosion of the emerged Animikean
n had gone on for a long period of time, flows of lava of unprec-
ed magnitude were poured out upon the surface of the land
considerable areas and intruded into the existing terranes. (9)
e the outflows ceased, sedimentation began again in the region
oon predominated. Even this long category of physical events
newhat inadequate, since there are local unconformities at various
s, representing minor disturbances of undetermined extent, and
minor changes are probably unrecorded, or their records unrecog-
.

will be seen that oscillations of level were one of the marked
eteristics of the Lake Superior region during the Proterozoic
It will be seen in the sequel that this is a characteristic confined
er to this period nor to this region. All geological history indi-
that changes of the relations of sea and land are among the nota-
ents of the earth's history, from the beginning even to the present
Since many other changes are dependent on them, they are
ht to furnish the best basis for the subdivisions of earth history.

is not now possible to determine, even approximately, either the
or the vertical extent of the crustal oscillations which took place
g the Proterozoic era, but the extent of the area in North America
n became land at the close of the Keweenawan—that is, at the
of the Proterozoic—has been estimated with sufficient accuracy
ake its cartographic representation instructive (Fig. 90).

etamorphism.—It has been pointed out that the Huronian rocks
on the whole, more highly metamorphosed than the Animikean,
the Keweenawan formations are metamorphosed scarcely at all.
he other hand, the Animikean beds are locally as highly metamor-
as the Huronian, indicating intense dynamic action, at least locally,
the deposition of the second great system. Since different sorts
ck behave differently under dynamic action, it follows that some
are much more highly metamorphic than others associated with
, even though subjected to the same forces. Independent of
ences due to variations in the character of the rock, metamorphism
sually been intense about massive intrusions of igneous rock.

here is scarcely a phase of metamorphism which the Proterozoic
do not show. The schists, slates, and gneisses are especially
roduct of dynamic metamorphism; the quartzites are the products

of extreme consolidation by cementation; the iron ore is of metasomatism, effected by ground waters; while oth metamorphism are due to the heat of intruded rock. It understood that the metamorphism of any considerable l is effected by any one process alone. Dynamic action, on the whole the most important force in metamorphism, ates heat, and high temperature, especially in the prese facilitates change. So, too, in the case of igneous intr is often great dynamic action as well as great heat, an agent of chemical change, is always present.

Sequence of events elsewhere.—A consonant but no identical series of events was probably in progress abou Archean area in North America, and in the world, during zoic era; but it does not follow that about every other area three great systems of rocks were laid down during About some such areas there may well have been two ins systems of Proterozoic rocks, while about others, continu tation may have been in progress from the beginning of period to the end of the Keweenawan. Each Archean lan cially if distant from others, may have had an indepen though the great deformative movements were probably is probable therefore that adjacent Archean areas were the same sequence of events, though not necessarily to the The greater the separation of regions, the less closely are t likely to correspond.

PROTEROZOIC ROCKS IN OTHER REGIONS.

Pre-Cambrian sedimentary formations occur in man of North America[1] in relations to the Archean similar to described. On the whole, it may be said that they resem of the Proterozoic systems about Lake Superior as clo be expected under the general principles already enunciat cases they appear in surface association with the Archean cases no such relation exists.

There are several ways in which the areas of expose k, not in surface association with the Archean, may have arisen.

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[1] For references, see foot-notes, pp. 204 to 215.

If after the deposition of the Proterozoic systems the strata re folded, certain portions might have been brought above sea level, stituting land. If such areas were never buried, the present exsure of the Proterozoic rocks would be explained. (2) Again, ing the long period of erosion which succeeded the uplift following time of Proterozoic sedimentation, the surface may have had its ography greatly changed. If it were brought to the condition of peneplain with pronounced monadnocks standing upon it, as in th-central Wisconsin, later sedimentation, accomplished during a sequent period of submergence, may have failed to bury these rations. Isolated outcrops of Proterozoic might represent such reduced areas. (3) Or, still again, if the monadnocks were buried, sion may have since removed the beds which were deposited over m. (4) Uplift and erosion of any surface beneath which the Algonn rocks lay, would have exposed them without exposing the Archean, rosion were sufficiently deep to remove all overlying beds, and not deep as to reach the Archean below.

The following general statements concerning the Proterozoic of ferent localities give some idea of its extent and relations:

North of Lake Huron.—The Proterozoic formations of this region have already n referred to (p. 181). The Keweenawan series does not seem to be repreted, though it appears but a short distance to the west; but its absence vios no principles which have been enunciated. If lava here failed of extrusion, l if the region was not in the attitude necessary for sedimentation during the eenawan period, the corresponding system of rocks should be absent. The ta of this area are much less folded and metamorphosed than the correspondformations in many parts of the Lake Superior region, showing that dynamic on was not equally severe in different regions, and that the degree of metamorm is not a safe criterion by which to determine age.

The great northern area.—In the extensive area north of the Great Lakes, terozoic rocks are known to have wide distribution, and to be associated with larger areas of Archean. The former often occupy belts (troughs) in the er (see Fig. 65) and their separation is often a matter of difficulty. At some ts about Hudson bay, there appear to be three systems of rocks between the hean and Cambrian, though it cannot be asserted that these systems cornd with those farther south, and the corresponding names are not commonly ied to them. The several series appear to be separated from one another unconformities, and the lowest series is believed to be unconformable on Archean.

The eastern provinces of Canada.—At various points in east
the province of Quebec, in New Brunswick, Nova Scotia, and
the Proterozoic systems of rocks are represented. In the easte
Canada, there appear to be three series of pre-Cambrian rocks, so
certainly Proterozoic. Their relations, however, have not been fu
Proterozoic rocks occur in New Brunswick, and in the southern p
ince there appear to be at least two unconformable series of th
Scotia, the Proterozoic system seems to be represented by abou
sedimentary rocks. In Newfoundland there is a pre-Cambri
series about 10,000 feet in thickness which is probably Proter
of this eastern region, the work has not been sufficiently detail
definitely the relations of the Proterozoic and the Archean, or
strate the presence of the latter. In some places the Protero
are highly metamorphic, and in others they have suffered litt
induration.

The original Laurentian area.—In the area where the name
first applied, the area north of the Ottawa and St. Lawrence
the cities of Montreal and Ottawa, there is a series (the Grenville
metamorphic rocks, formerly known as the Upper Laurentian. T
series have been so profoundly metamorphosed that all traces
structure are lost, but their composition and general relations le
that they orginally consisted of sedimentary beds and igneou
age is not established, but they are tentatively referred to the e
Nowhere does a series of rocks better illustrate the effect of dy
phism. Not only were the rocks closely folded and subjected to
which accompany close folding, but along certain planes they
fragments, and by movements along these planes the resistant
rounded so as to resemble pebbles. Thus arose layers resemblin
On re-cementation, such rocks are called *autoclastic*. In many c
were subsequently flattened by the intense pressure to which
jected. The Proterozoic of this district, so far as known, consists
on which the Cambrian rests unconformably.

In *the Hastings district*, southwest of Ottawa, there is a P
similar to that of the original Laurentian area, except that th
highly metamorphic. They overlie the Archean unconformably.

The rocks of Canada here classed as Proterozoic are
ferent regions by different names. To them the ter
Huronian, Grenville, and Upper Laurentian have been
time and another in different parts of the Dominion. Fr
it has often been reported that they are conformable on
instead of unconformable; but where detailed work ha

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[1] Adams, Am. Jour. Sci., Vol. L, 1895, pp. 58–69; and Vol. III, 18
also Trans. Roy. Soc. Canada, 1899 and 1901.

on by the more refined methods of the present time, an unconformity has generally been found. The unconformity is evident wherever the overlying system is not highly metamorphosed; but where the strata have been much folded and subjected to the changes which profound dynamic action always brings in its train, they have sometimes become so thoroughly crystalline and so complex in structure that they are not easily differentiated from the Archean in the limited exposures which are open to observation. The fact that the Archean was affected by the same dynamic action which metamorphosed the Proterozoic rocks tends to give the two systems uniformity of structure where both have been profoundly altered.

The Adirondack region.[1]—Rocks believed to be of Proterozoic age make up the larger part of the Adirondack mountain mass. These rocks belong to two groups: (1) The central mass of the mountains, made up of a complex of igneous rocks which were intruded into (2) a series of pre-Cambrian meta-sedimentary rocks. The igneous rocks sometimes contain bodies of clastic rock. The igneous rocks are of various types (granite, syenite, anorthosite), and are massive in some places and much foliated in others. The clastic series into which the igneous rocks were intruded surround and lap up about the base of the igneous mass. They include crystalline limestone, and quartzose, sillimanitic and graphitic gneisses, together with some gneisses believed to be meta-igneous. The limestone (marble) associated with the gneisses is often massive, a structure which suggests either that it was completely crystallized under static conditions subsequent to the dynamic action which effected the metamorphism of the other sorts of sedimentary rock,[2] or that it behaved very differently from the other sorts of rock when metamorphism was in progress. The metamorphism of the clastic series was probably largely effected at the time of the intrusion of the igneous rocks. The meta-sedimentary rocks are thought to be the equivalent of the Grenville series of Ontario. The floor on which these sedimentary rocks were laid down has not been discovered.

Isolated areas in the Mississippi basin.—Proterozoic rocks come to the surface in isolated areas at several points in the basin of the Mississippi east of the Rocky mountains (Fig. 38). There are some small areas of Animikean (?) quartzite in south-central Wisconsin (the Baraboo quartzite),[3] and in the southeastern corner of South Dakota [4] and adjacent parts of Minnesota and Iowa (the Sioux quartzite) (Fig. 80). In the former place the quartzite has no association with

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[1] Cushing. 54th Ann. Rept. N. Y. State Museum, Vol. I, pp. 258–282; and Kemp, 13th Ann. Rept. N. Y. State Geologist, 1893, pp. 444, 445.

[2] Van Hise, Principles of Pre-Cambrian Geology, 16th Ann. Rept., U. S. Geol. Surv., p. 771.

[3] Irving, Geol. of Wis., Vol. II, pp. 504–519. This may be the Middle Huronian of p. 161. Weidman, Bull. XIII, Wis. Geol. Surv. 1904.

[4] Todd and Hall, Alexandria (S. D.) folio, U. S. Geol. Surv.

Archean, so far as surface exposures show, and in the latter but litt localities there is igneous rock associated with the sedimentary. quartzite has been metamorphosed by dynamic action into quartz 81). In these places, and especially in Wisconsin, the superior har quartzite, as compared with the surrounding Cambrian sandstone, h development of striking topographic features. Post-Cambrian erc moving the later formations, has again exposed the pre-Cambrian of Baraboo quartzite, much as they were before being buried bene sediments.

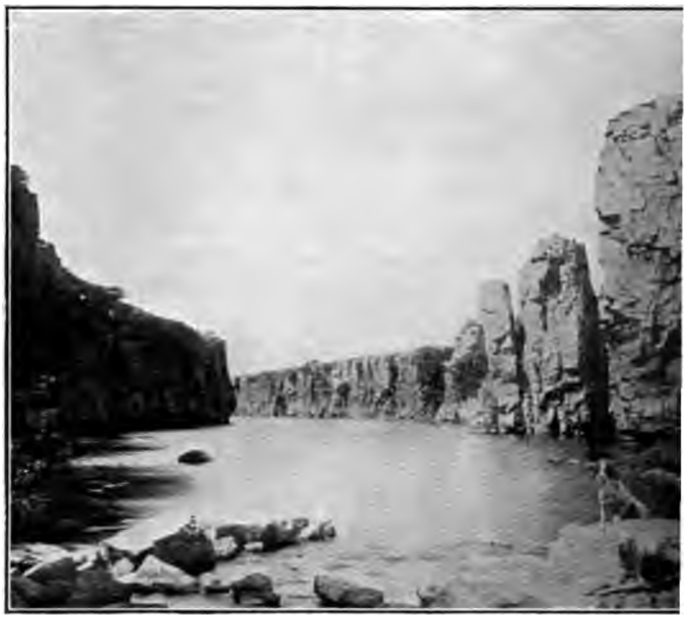

Fig. 80.—The Palisades, Minnehaha County, S. D. Sioux quartzite. (
Ia. Geol. Surv.)

Rocks of probable Proterozoic age are also known in the Black] Dakota,[2] making the core of the mountains, and occupying an a miles long by 20 broad. They consist of closely folded meta-sedim such as mica slates, quartzites, schist-conglomerates, ferruginous schists and gneisses, and intrusive masses of granite and basic rock granite batholiths, the largest of which is eight or ten miles long broad, numerous dikes penetrate the clastic beds. The latter affo

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[1] Van Hise, Jour. of Geol., Vol. I, pp. 347–355.

[2] In addition to general references, see Jaggar, 21st Ann. Rept., Geol. Surv.

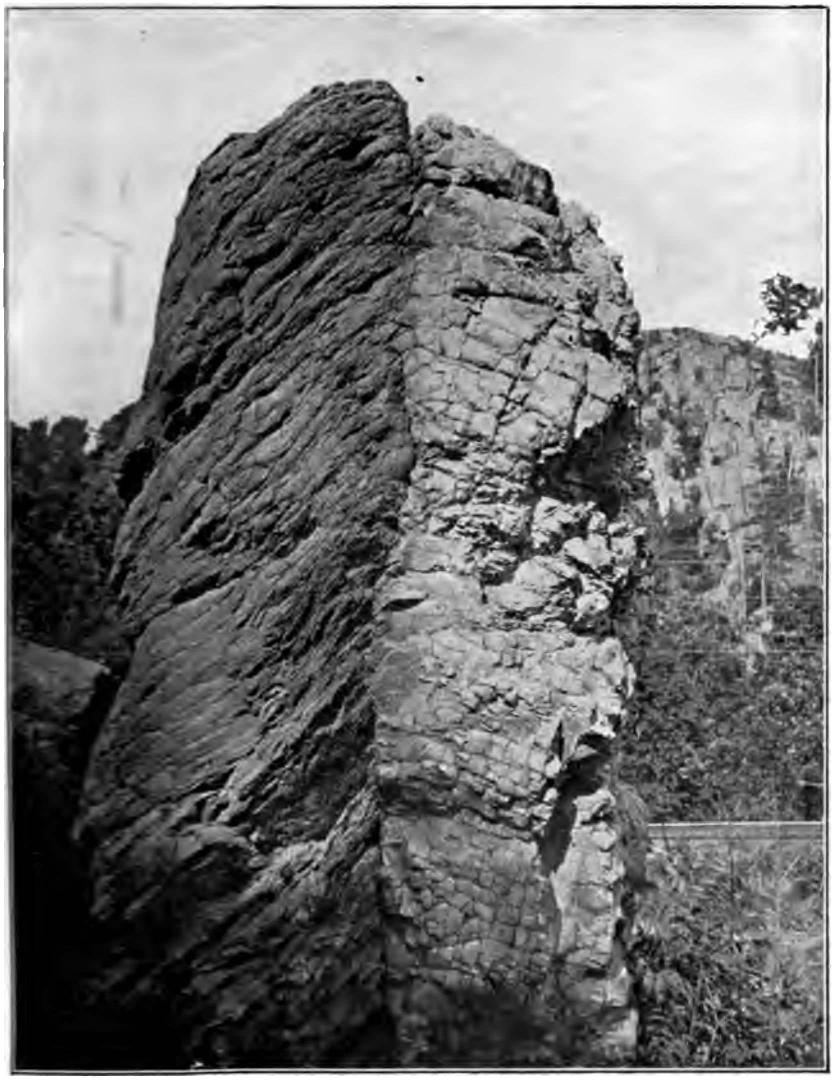

FIG. 81.—Fracture cleavage developed by pressure shown in the left half of the figure, while it is wanting in the right half. The vertical line is a bedding plane. The layer to the left was of sufficiently different composition, or subject to sufficiently different movement, to develop fissility, while that to the right was broken (brecciated) instead. The rock at the left would be called quartz schist, while that at the right is quartzite. Animikean formation near Ableman, Wis. (Atwood.)

trations of the metamorphosing effects of igneous intrusions.
phism is not contact metamorphism in the ordinary sense, but se

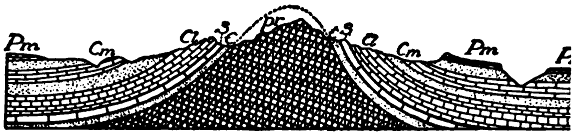

Fig. 82.—A section through Crow peak in the Black Hills region, sho Hills type of structure. *pr*, igneous rock (porphyry); *Є*, Cambri (Ordovician); *Cl* and *Cm*, Carboniferous formations; *Pm*, Permi section, 1½ miles. (Jaggar, U. S. Geol. Surv.)

combine cementation, injection, metasomatism, and mashing.[1] T intrusions is not known. Figs. 82 and 83 are sections of laccolit

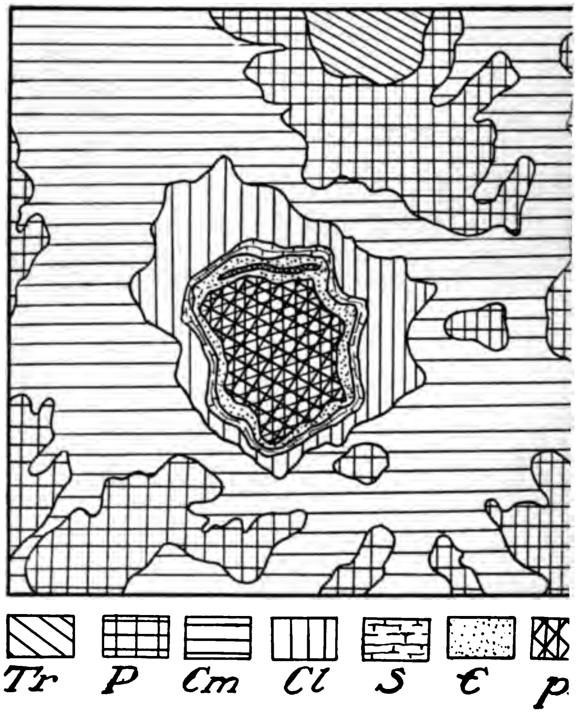

Fig. 83.—Map of the region shown in section in Fig. 82. *pr*, porphyr *S*, Silurian (Ordovician); *Cl* and *Cm*, Carboniferous formation *Tr*, Triassic. (Jaggar, U. S. Geol. Surv.)

Black Hills region. They illustrate in a small way the structur Hills. Fig. 83 is a map of the area of which Fig. 82 is a secti

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[1] Van Hise, 16th Ann. Rept. U. S. Geol. Surv., Pt. I, p 8

Though Archean rocks have not been identified in association with the Proterozoic system of this region, it does not follow that the latter were not derived from the former, so far as they are sedimentary. The lands which gave rise to the sediments appear to have sunk and been buried at some later time, and not again exposed by erosion. The Proterozoic rocks of this region were long buried by formations of lesser age. The uplift permitting the erosion which discovered the older rocks is a relatively recent event (see Tertiary periods).

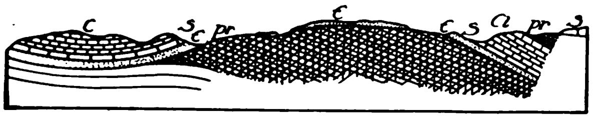

FIG. 84.—Section through Kirk Hill in the Black Hills region, illustrating the type of structure shown in Fig. 82. Legend same as in Fig. 82. Length of section, 3 miles. (Jaggar, U. S. Geol. Surv.)

The Proterozoic system is represented in at least one locality in eastern Wyoming.[1] The rocks are quartzites, schists, silicious limestone, and gneiss, and are locally (near Guernsey) iron-bearing. They have also yielded some copper.

In southeastern Missouri (St. Francis mountains) there are several small areas of pre-Cambrian rock, both sedimentary and igneous. They are not associated at the surface with recognized Archean rock, and their relation to the Proterozoic rocks of other regions has not been determined. As in the Black Hills, the Proterozoic formations of this region were probably buried by younger formations, and their exposure at the surface is the result of erosion following subsequent uplift. The uplift in this area was probably much earlier than that in the Black Hills.

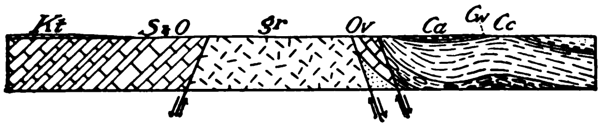

FIG. 85.—Section showing the relations of the Tishomingo (I. T.) granite. *Gr*, pre-Ordovician; *Or* Ordovician (Viola limestone); *S* and *O*, Silurian and Ordovician (Sylvan shale); *Cc*, (Caney shale); *Cw*, (Wapanucka limestone); and *Ca*, (Atoka formation) Carboniferous; *Kt*, Lower Cretaceous (Trinity formation), Length of section, 5 miles. (Taff, Atoka, I. T. folio, U. S. Geol. Surv.)

In Texas there is at least one series (Llano) of Proterozoic sedimentary rocks, partly metamorphic, associated with igneous rocks which may be Archean. An extensive area of granite (Tishomingo granite) in Indian Territory[2] is also believed to be of pre-Cambrian age (Fig. 85).

The Cordilleran region.—In this region the axial cores of many of the older mountain ranges are believed to be of Archean rock. In many of them there are thick series of sedimentary or meta- rocks overlying the Archean, and overlain by Cambrian strata. Where the post-Archean formations are not overla Cambrian strata, their Proterozoic age is sometimes op tion. In some places they are highly metamorphic, and i slightly so.

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[1] W. S. T. Smith, Hartville, Wyo., folio, U. S. Geol. Surv.

[2] Taff, Tishomingo (I. T.) folio, U. S. Geol. Surv.

Rocks referable to the Proterozoic systems are found in the range and in some of other mountains of Wyoming; in the Brid

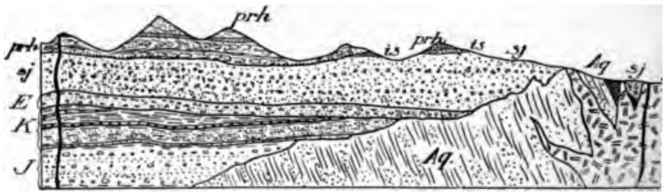

Fig. 86.—Section showing the relations of the Proterozoic formations region of Colorado. *Aq*, Proterozoic quartzite; *J*, Triassic an Cretaceous; *E*, Eocene; *sj*, San Juan series (tuff, breccia, etc.) rhyolite; *gd*, gabbro diorite. Length of section, 5 miles. (U. S.

Belt mountains [1] (Belt series, fossiliferous [2]) in Montana, in the Livingston ranges, near the National Boundary, where they a and some 10,000 feet thick [3] (Fig. 46), and at a few other points in t in British Columbia; in the Wasatch and certain lesser mountain in several of the ranges of Nevada [5] (Shell Creek, Egan, Pogoni in the Front, Sawatch, Uncompahgre, and Quartzite ranges of Co the Grand Canyon of the Colorado in Arizona.[7] In most if not all ties the sedimentary beds predominate, but are accompanied b which are in part contemporaneous in origin. The thickness zoic rocks in these various localities is often great, but general

In the Canyon of the Colorado (Arizona) the succession of pr mations is easily studied, because of the extensive exposure Canyon group [8] (Proterozoic), more than 10,000 feet in thickne formably on the Archean, and is in turn covered unconformabl brian. This great group is itself divisible into two systems by formity.[1] The general relations are shown in Fig. 88. Here, as in Montana. a few fossils have been found.[2]

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[1] See Little Belt, Livingston, and Three Forks folios, U. S. Geol. S

[2] Walcott, Bull. Geol. Soc. Am., Vol. 10, pp. 227–44.

[3] Willis, Bull. Geol. Soc. Am., Vol. 13, pp. 316–24.

[4] Weed, 22d Ann. Rept. U. S. Geol. Surv., Pt. II, p. 434. See Belt, Livingston, and Three Forks (Mont.) folios, U. S. Geol. Surv

[5] King, Geol. Expl. of the 40th Parallel, Vol. I.

[6] Proterozoic (Algonkian) formations are shown on the Pike's Pe folios (U. S. Geol. Surv.) of this State.

[7] See references in Bull. 86, U. S. Geol. Surv.

[8] Powell, Geology of the Uinta Mountains.

In many of these localities the Proterozoic strata are associated with Archean, but the details of their structure and relationships have not been worked out in many places. Enough, however, is known to render it probable that many of these localities, as British Columbia, southwestern Montana, the Wasatch mountains, etc., were within the limits of one geological province in the Proterozoic era. One of the features common to much of this province is the conformity of the Proterozoic strata beneath the Lower Cambrian. Within the province, a succession of formations and events as definite as those of the Lake Superior province will probably be established when the several areas have been studied with equal care; but the order established for this province may not be very similar to that of others, since the sequence of events in different provinces is not necessarily the same.

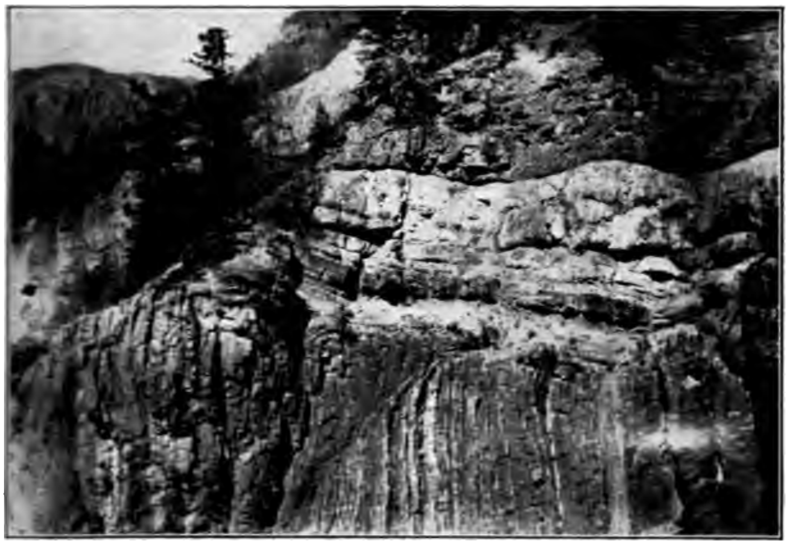

FIG. 86a.—Horizontally-bedded limestone, resting unconformably on vertical beds of Proterozoic Quartzite. Box Canyon, near Ouray, Colo. (R. T. Chamberlin.)

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[1] Walcott, 14th Ann. Rept. U. S. Geol. Surv. and Bull. 30, U. S. Geol. Surv. Walcott gives a three-fold division of the Algonkian.

[2] Walcott, Bull. Geol. Soc. Am., Vol. X.

In the eastern part of the United States.[1]—In the east the United States there are large areas of metamorphic were formerly classed as Archean. As shown in Fig. 38,

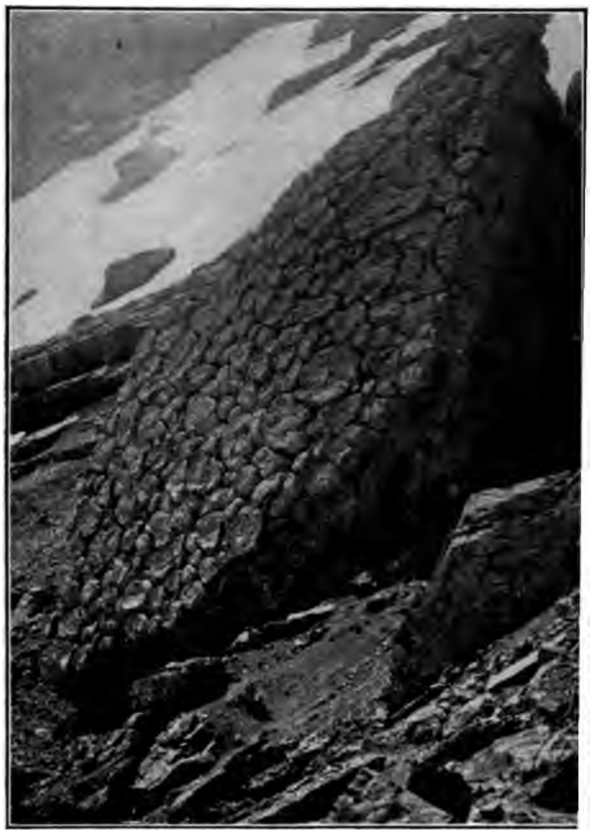

FIG. 87.—Figure showing peculiar polygonal structure in Proterozoi northern Montana. (Willis, U. S. Geol. Surv.)

occupy a large part of New England, the southeast co York, and parts of northern New Jersey, the South Mou in Pennsylvania, and farther south, the wide belt of t plateau lying east of the Appalachian mountains from on the north to Alabama on the south. This belt of rocks contains formations that were sedimentary, and tho igneous. In some places they are so far metamorphosed as to have lost all trace of their original texture, while in others the change is much less complete. Within this belt of crystalline rocks, Proterozoic formations are believed to occur, but they have not been generally differentiated from the Archean on the one hand, and from the metamorphic Paleozoic rocks on the other.

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[1] See Bull. 86, U. S. Geol. Surv., and folios, U. S Geol. Su

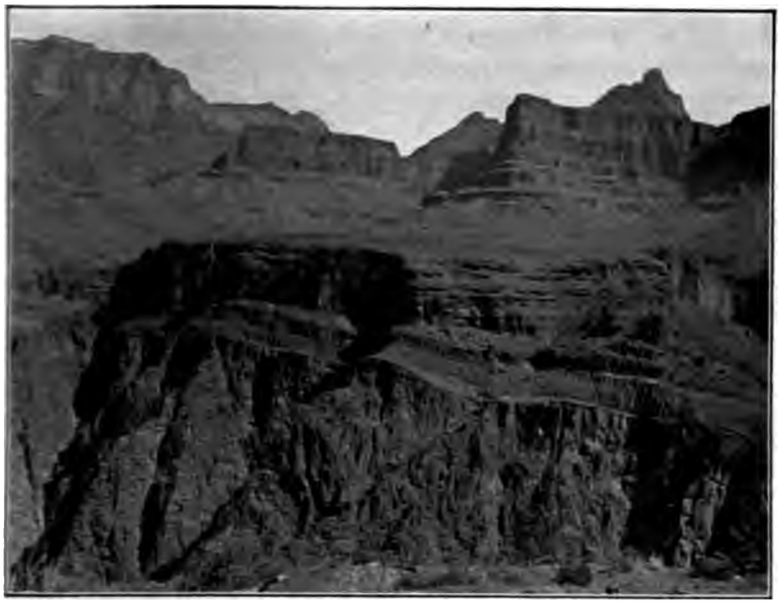

FIG. 88.—Figure showing the Archean, Proterozoic, and later formations at one point in the Grand Canyon of the Colorado in northern Arizona. The lowermost nonstratified formation is Archean. The horizontal beds in the upper part are Paleozoic, their basal portion being Cambrian. The tilted beds between the Archean and Paleozoic are Proterozoic. (Atwood.)

In the Green mountains of Vermont, there appear to be two series (the Mendon and the Mount Holly) of sedimentary or meta-sedimentary rocks of complicated structure, unconformable beneath the Cambrian.[1] Patches of pre-Cambrian rock are known in thirteen places in western Massachusetts, but they are separated with difficulty from the Cambrian, Silurian, and Devonian beds which were metamorphosed with them. They consist of gneisses, schists, and crystalline limestone[2] (Fig. 89). In southeastern New York there appear to be pre-Cambrian metamorphic rocks of complicated structure (Fordham gneiss) closely associated with metamorphic rocks of lesser age. In places the gneiss is par ary and partly of igneous origin, developed by the parallel injec materials into a sedimentary series. The crystalline rocks of of northern New Jersey appear to be chiefly Proterozoic. Th igneous and sedimentary rocks. Among the latter are limes graphitic gneisses, and large bodies of iron ore, all of which point [illegible] the time the beds were deposited. In the South Mou Pennsylvania the Proterozoic seems to be represented by igneous [illegible] Cambrian rests unconformably. [illegible] the [illegible] the Archean system [illegible] certainly identified, nor has the Proter rocks [illegible]

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[1] Whittle, cited by Van Hise, 16th Ann. Rept. U. S. Geol. Surv., Pt. I, p. 827.

[2] Ibid., p. 830; and Emerson, Holyoke, Mass., folio, U. S. Geol. Surv.

[illegible]

nters of sedimentation, as to correspond. Igneous rocks form a t inconsiderable part of the Proterozoic systems, and there is no w requiring igneous activities in different regions to correspond ither in time or in the nature of their products. Even body deformations, which are much the most general and which are the basis for the subdivision of the systems, need not have corresponded in their particular phases, in different regions. It follows (1) that the number of series within the Proterozoic in one place may not be the same as in another; (2) that the thicknesses of the various systems may vary within wide limits; (3) that there need have been no close correspondence in the sorts of rock in different regions at the outset; and (4) that they may have been metamorphosed unequally since their deposition. The dissimilarity of the Proterozoic in different regions, as suggested by the preceding sketch, was, therefore, to have been anticipated.

PROTEROZOIC FORMATIONS IN OTHER CONTINENTS.

Little need be said of the Proterozoic systems of other continents, but they are believed to exist in Great Britain,[1] where the Torridonian sandstones (8,000–10,000 feet thick in Scotland) and perhaps the Dalradian series may be Proterozoic; in France,[2] where phyllites, graywackes, quartzite, sericitic schists, and igneous rocks with an aggregate thickness of several thousand meters, are regarded as Proterozoic; in Spain, where phyllites, hälleflinta, and quartzite represent the era; in Germany, where mica schists predominate below, and phyllites above;[3] in Finland,[4] where nearly 3000 meters of conglomerates, quartzites, schists, limestone, and diorite lie between the Archean and the Cambrian; in Scandinavia (Sweden), where there are similar thicknesses of similar rocks occupying a similar stratigraphic position; and probably in India and Brazil. In more than one of these countries, the pre-Cambrian sedimentary rocks are thought to belong to at least two

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[1] Sir Archibald Geikie, Jour. of Geol., Vol. I, and Text Book of Geology, 4th ed., Vol. II.

[2] De Lapparent, Traité de Geologié.

[3] Gümbel, Grundzüge der Geologie, pp. 511–522.

[4] Sedersholm, Ueber eine archäische, Sedimentformation in südwestlichen Finland, Bull. de la Commission Geologique de la Finlande, No. 6, 1897.

systems, separated by unconformities. It is worthy
in Sweden[1] iron ore occurs, as in the Huronian of L
Little has been done toward the correlation of the pre-Ca
of Europe and America. It is significant, however, th
Algonkian and Proterozoic are being adopted[2] in the d
the pre-Cambrian formations on geological maps. As
the Proterozoic rocks of Europe contain occasional fo
their number is small.

In the province of Shan-si, China, there are at least t
terozoic systems, separated by an unconformity. The lo
composed of meta-sedimentary rocks, closely folded; the u
what folded and slightly metamorphosed. The lower sy
the Archean, and the upper underlies the Middle Cam
formably.[3]

LIFE DURING THE PROTEROZOIC ERA.

While the Proterozoic rocks do not generally contain
can be no doubt that life existed during the era. The dir
are as follows: (1) The carboniferous shales, slates, and
cate the existence of life; (2) the occasional fossils[4] (
Montana and in the Grand Canyon of the Colorado in Ari
strate the existence of life at that time; (3) the iron ore
tems, although not originally deposited in its present fo
imply the existence of life, both when it was accumulate
it was transformed into its present condition; and (4), t
It should be noted that limestone occurs in the Huro
and that it is, in some places, near its base. The limestone
regarded as demonstrative of the existence of life, but in
the belief has gained ground that considerable formati
stone may have originated by precipitation from sea-
origin is suspected for many limestone formations which

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[1] Törnebohm, Grunddragen af det Centrale Skandinaviens Bergbyg

[2] Bäckström, Vestanafältet (The Vestana region), 1867.

[3] Willis and Blackwelder, Carnegie Institution. Unpublished data.

[4] For summary of knowledge concerning pre-Cambrian fossils, see
Geol. Soc. Am., Vol. 10, pp. 199-244.

fossils, and if this hypothesis is applicable to any extensive formation of limestone, it may be applicable to those of the Proterozoic systems. But even without reliance on the limestone, the fossils leave no doubt of the existence of life in the Proterozoic era.

The best-preserved fossils are those of eurypterus-like crustacea. There are also tracks of two genera of annelids, and other undetermined forms. Besides these certain fossils, there are obscure forms which appear to be referable to brachiopods and pteropods. It is significant that the oldest definite fossils yet found are well-developed crustacea, forms well up in the animal kingdom.

CLIMATE.

Since inferences concerning the climate of any period are drawn chiefly from fossils, and since fossils are exceedingly rare in the Proterozoic strata, there is little warrant for any conclusion concerning the climate of the period. Certain pre-Cambrian conglomerates of Ontario, shown in the Cobalt region and elsewhere, have been interpreted recently, as of glacial origin, but the evidence thus far presented does not seem to be conclusive on this point.

[1] Coleman. Geol. Soc. Am., 1906.

CHAPTER V.

THE CAMBRIAN PERIOD.

FORMATIONS AND PHYSICAL HISTORY.

THE great crustal movements which brought the Pro a close converted a large area within the limits of the N continent into land. This is shown by the geographi and the stratigraphic relations of the next succeedi sedimentary rocks. This system, *the Cambrian,*[1] is the of rocks now recognized as having been deposited duri zoic era.

Where the base of the Cambrian system in North Am sible, the system is, as a rule, unconformable on underlyi (Figs. 88 and 89). Where this is the case, it is inferred

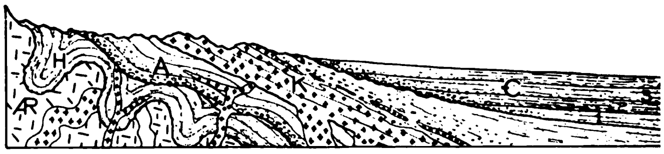

FIG. 89.—Diagram representing the general relations between the C the Proterozoic formations. The diagram is based on the genera exist in the Lake Superior region.

face on which it rests was a land surface and exposed a time before the formations above the unconformity w Furthermore, the attitude of the Proterozoic strata is su that they were locally much disturbed prior to the n which preceded the deposition of the Cambrian bec

Were the total area where the Cambrian system is on its base known, it would furnish a basis for estimati of the withdrawal of the sea from the continent at th Proterozoic era, and before the deposition of the known it were possible, on the other hand, to determine the ex covered by formations of the Cambrian system, this

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[1] A summary of the literature on the North American Cambri is given by Walcott in Bull. 81, U. S. Geol. Surv.

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ASTOR, LENOX AND
TILDEN FOUNDATIONS
R L

[illegible] are thought to represent approximately [illegible]

[1] Recently proposed by the U. S. Geol. Surv., 24th Ann. Rept., p. 27, to take the e of Potsdam.

[2] Not much used except in Minnesota.

the maximum area covered by the Cambrian seas, for the ormations were, so far as known, laid down on the floor of f the exact area of the sea at any stage of the Cambrian determined, the exact area of the land at the same stage ously be known. If these data could be determined for of the period, they would constitute the record of its geonges, so far as distribution of land and water is concerned. minations cannot be made for every stage of the period, imations may be made for certain stages, and these approxie a valuable insight into the geography of the times.

DIVISIONS OF THE CAMBRIAN AND THEIR DISTRIBUTION.

nbrian period has been, for convenience, divided into three ı may be called the Earlier, the Middle, and the Later divisystem of rocks deposited during the period has been divided orresponding series, known as the Lower, Middle, and Upper espectively. Other names are sometimes assigned to these Thus Georgian (Vt.), Acadian, and Potsdam (N. Y.), names where the corresponding divisions of Cambrian were first ıdied, are synonyms for Lower, Middle, and Upper Cambrian , as these terms are used in North America. Saratogan[1] ix[2] are also used as synonyms for Potsdam. The approxibution of the beds of sediment laid down in each of the ons of the period is known, and the variations in the disthe three series record the changes in the relations of land luring the Cambrian period.

The Lower Cambrian.

tion.—Fig. 90 shows the known surface distribution of the Middle Cambrian (Georgian and Acadian) series. The ıns represent the areas where these series come to the surface. haded with lines represent the areas within the limits of the vhere the same series are believed to occur, though now ıe longer the lines, the better the basis for the inference both series are present. North of Mexico, the unshaded ı in the figure are thought to represent approximately the

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proposed by the U. S. Geol. Surv., 24th Ann. Rept., p. 27, to take the lam.

h used except in Minnesota.

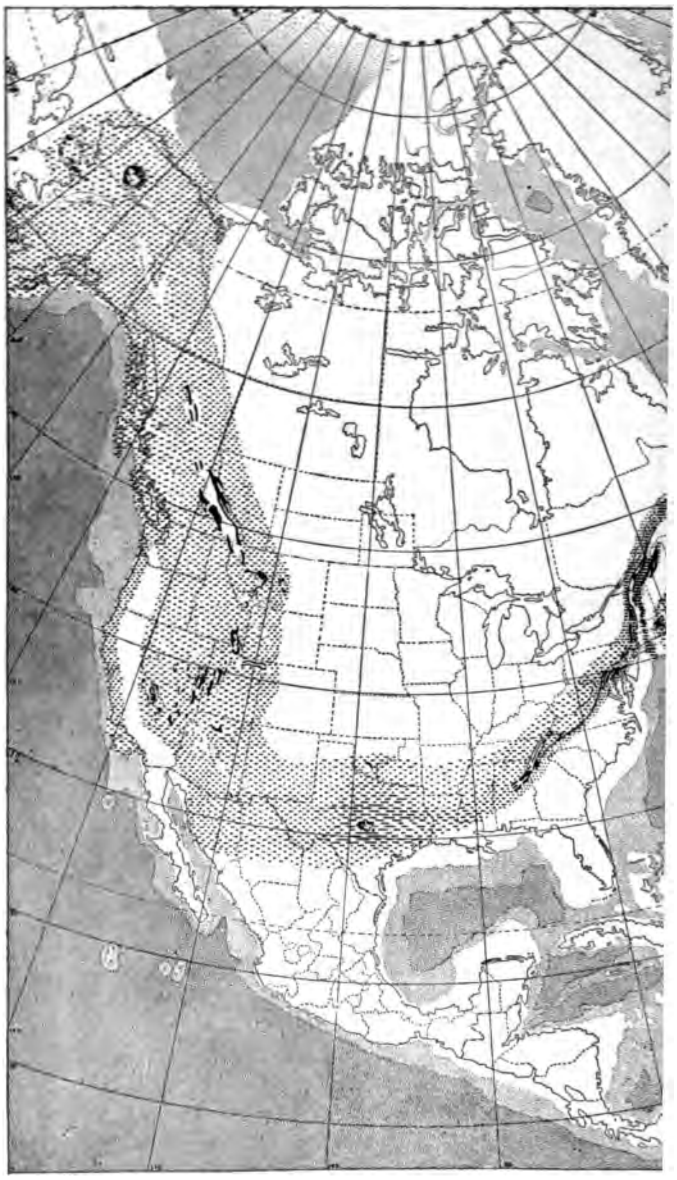

FIG. 90.—Map showing the outcrops (in black) of Early and Middle tions. The areas shaded by lines represent regions where tl believed to exist, though not exposed. The longer the lines basis for belief in the existence of the beds. The unshade Mexico are believed to have been land during the early portion period. The unshaded area south of the United States represe edge. The shading within the area of the ocean is the same as

eas which remained above the sea up to the end of the Middle Cam-ian. In Mexico and Central America, the blank area represents ck of knowledge. Since the distribution of the Lower and Middle ambrian series is much the same, the black areas of the map may e taken to represent the surface distribution of the Lower Cambrian ithout serious error, if the areas in Arizona, Oklahoma, and Texas e excluded. On account of later erosion, the Lower and Middle ambrian strata are probably not now present over the whole of the rea on which they were originally deposited.

So far as these formations contain marine fossils, it is safely inferred hat the areas where they now occur were occupied by the sea at some ime during the early and middle portions of the Cambrian period.

As the map shows, the Lower Cambrian is known on the coast of abrador, in Newfoundland, at various points between these localities nd Maine, at several places in New England, at many points in the Iudson-Champlain valley, and at various points in the Appalachian nountains between the Hudson and Alabama, but is generally absent rom the area east of these mountains. From the distribution of the ower Cambrian series in the east, and from its fossils, it is inferred that great sound existed in early Cambrian time near the southeastern order of the continent, extending from Labrador to Alabama.[1] This ound is believed to have been shut off from the Atlantic by land which ccupied a large part of the site of the present Piedmont plateau, ut whose eastern limit is unknown.

Lower Cambrian formations, with fossils of marine organisms, are lso known in Nevada, Utah, western Montana, Idaho, and in some arts of British Columbia, from which it is likewise inferred that the sea ccupied portions of western North America during the same epoch.

The absence of Lower Cambrian strata from other regions is hardly ess significant than their presence in those mentioned. They are elieved to be wanting in most of Montana, in Wyoming, Colorado nd Arizona, and in the territory east of these states nearly to the ppalachian mountains.[2] Not only are they absent now, but they ppear never to have been present, and this leads to the inference that most of the great area between the Appalachian moun east and the Rocky mountains on the west was above th the early part of the Cambrian period.

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[1] Ulrich and Schuchert, Bull. 52 (Paleontology 6) New York State Museum, Report f the State Paleontologist, 1901, pp. 635–6.

[2] Comstock (First Ann. Rept. Geol. Surv. of Texas, 1889, pp. 285–292) thinks ower Cambrian occurs in Texas.

Geography of the Early Cambrian.—On the basis of th tribution of the Lower Cambrian strata as cited above, that there was an extended land area within the lim America in the early part of the Cambrian period, and fr spread unconformity of the Lower Cambrian on its bed, that this area was still more extensive just before the dep known Lower Cambrian. The map (Fig. 90) shows, as is now known, the area of land and water within the a America during the early part of the period.

"Lost" interval.—Where the Cambrian is unconform Cambrian formations there is a break in the geological r breaks are sometimes said to represent "lost" intervals, which are "lost" being the periods elapsing between the the beds below the unconformity, and those above. tion for such an interval is only partly true, for in the itself there is the record of exposure and erosion, followed ence and deposition. The general sequence of events is to this extent the record is not lost. On the other hand, of the recorded erosion were deposited elsewhere, consti formation. Wherever the sedimentary beds deposited erosion interval represented by an unconformity are record of the interval is certainly not open to inspection regarded as "lost," or as too well preserved.

The relations and principles involved are illustrated by Figs. the line *AA′*, Fig. 91, represent the sea-level at the beginning of t closed the Proterozoic era, while *CC′*, Fig. 92, represents the sa time of maximum post-Proterozoic uplift. While the water-leve from *AA′* to *CC′*, sedimentation was in progress beneath the wat and at all stages the sedimentary beds were essentially conform mations below. So long as the sea-level stood at *CC′*, depositior to the right of *C*, the beds being conformable on their substratum

Later, as the stratigraphic relations of the Lower Cambrian f the sea again advanced on the land, and as the shore line was toward *A* (Fig. 92), sediments were in process of deposition on th had recently been land, but which was now submerged. The d this stage between *C* and *A*, Fig. 93, were unconformable on beneath, though the corresponding deposits to the right of *C* w on their base. It is manifest that the unconformity between formations *Al* and 2 (Fig. 93) must represent a longer interval of time between *B* and *A* than between *B* and *C*, since the formation *Al* had been longer exposed in the former region. From *A* to *C* the section records a "lost" interval, but the deposits made during this interval (1, Fig. 93) are preserved to the right of *C*, though they may be inaccessible.

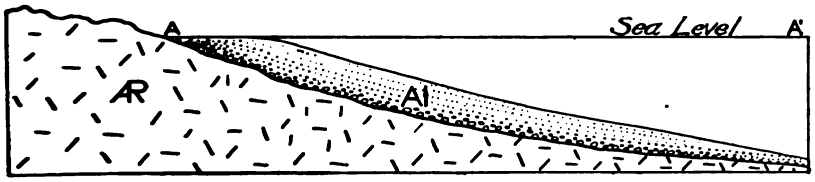

Fig. 91.—Figure showing a series of sedimentary rocks, *Al*, resting on and against older rock, *Æ*.

In the case under consideration, *Al*, deposited before the uplift, stands for the whole of the Proterozoic (Algonkian). As a matter of fact, the structure of the Proterozoic is much more complex than these figures show. (See Fig. 89.) Formation 2 (Fig. 93) is Cambrian. Formation 1, being inaccessible, is not classified. Were it accessible, its classification as Cambrian or as Proterozoic would probably depend on its fossils. Looked at from the physical point of

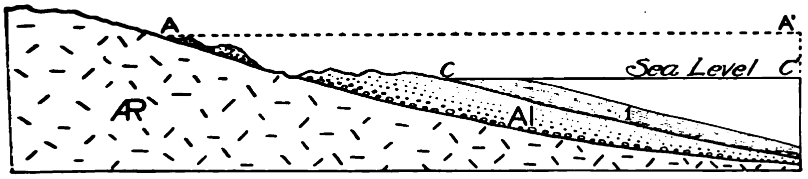

Fig. 92.—This figure represents the region shown in Fig. 91 as having risen, or the sea-level as having been lowered. Erosion has affected the upper portion of the formations represented by *Al*. Meantime deposition of the eroded material has taken place beneath the sea-level. These new deposits are represented by 1 in the figure.

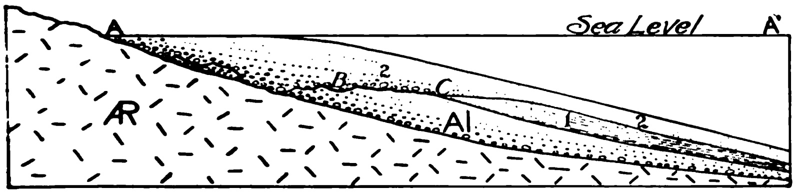

Fig. 93.—This figure represents the same region as Figs. 91 and 92 after the land has sunk so as to allow the sea to regain approximately the position which it occupied in Fig. 91. Younger sediments, 2, have buried the older, 1. The formation represented by 2 is unconformable on *Al* and on *Æ* but comformable on 1.

view, the question is, Shall the Proterozoic era be regarded as en
this region is concerned, (1) when the uplift preceding the Cambı
when it reached its maximum, or (3) when the subsequent subs
augurated? To this question no categorical answer can be given,
1 of Fig. 93 may be looked on as representing the time of trans
Proterozoic to the Cambrian.

Extent of unconformity at base of Lower Cambrian.—
northwest, the Lower Cambrian is generally unconformable
beds of Proterozoic age, but it seems certain that the Lo
must be conformable on the Proterozoic in areas which
ously under water (1) during the later part of the Proter
during the generally unknown interval between the Kew
Cambrian, and (3) during the Cambrian. Since it is im
the larger part of the area which was receiving sedime
last period of the Proterozoic era became land at the en
it follows that areas where conformity exists between C
Proterozoic are probably more extensive than areas wher
ity exists. From a study of the relations suggested by
it is apparent that unconformity between Proterozoic a
is likely to be most general just where their contacts are m
seen.

The Middle Cambrian.

The strata of the middle division of the Cambrian (
known to occur in the same general localities as those
both in the eastern and western parts of the continent, an
they occur in Texas, Oklahoma, Indian Territory,[1] Ari
some parts of Montana,[3] and possibly even in the western
consin[4] where Lower Cambrian is absent, or at any rat
This distribution indicates that the interior was being
the sea from the south and southwest before the close
Cambrian epoch. Like the preceding series, the Middle C
are generally absent from the eastern interior. Where
Cambrian rests on the Lower, as in the east and west, t

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[1] Taff, Professional Paper No. 31, U. S. Geol. Surv.

[2] Blake, Am. Geol. Vol. XXVII, p. 162; Walcott, Bull. Geol. So
p. 217.

[3] Walcott, idem., p. 209.

[4] Walcott, idem., p. 224.

are generally conformable.[1] Where it rests on pre-Cambrian formations, as in the States mentioned above, it is in unconformity with them. (Figs. 88 and 89.)

The Upper Cambrian.

In the Later Cambrian (Potsdam, Saratogan) epoch, the Appalachian region on the one hand, and the Cordilleran region on the other, were still submerged, as shown by the conformable (in general) superposition of the Upper Cambrian beds on the Middle Cambrian, in both regions. In addition, the Upper Cambrian beds are spread widely over the interior of the continent, indicating that the sea had extended itself greatly at the expense of the land in the Potsdam epoch. Where the Upper Cambrian rests on pre-Cambrian formations, it is in unconformity with them.

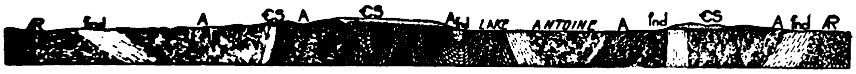

FIG. 94.—This figure represents a section in the Menominee region of northern Michigan, and shows the Potsdam sandstone, *Ꞓs*, in unconformity with Proterozoic formations, *A*. *Æ*, Archean. (Van Hise, U. S. Geol. Surv.)

Fig. 95 shows something of the distribution of the Upper Cambrian series. The black areas represent the areas where the series comes to the surface; the areas lined horizontally represent the areas where it is confidently believed to be present, though buried; the areas shaded by dashes are the areas where the series is probably present; while the dotted tracts represent the areas from which the series is thought to have been removed by erosion. The blank areas, except in Mexico and Central America, stand for the tracts which are thought to have remained above the sea throughout the Cambrian period;[2] in those countries, they represent lack of knowledge.

SECTIONS OF THE CAMBRIAN AND THEIR INTERPRETATION.

Fig. 96 represents known sections of the Cambrian formations in various localities.[3] The study of these sections, while involving

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[1] Ulrich and Schuchert think that the Appalachian synclinorium of Early Cambrian time was largely drained at the close of that epoch. Loc. cit., p. 636.

[2] Since this map was prepared, Upper Cambrian beds have been reported from southwestern Texas. Richardson, Reconnaissance in Trans Pecos, Texas, Bull. 9. Univ. of Tex. Min. Surv.

[3] Walcott, Bull. 81, U. S. Geol. Surv.

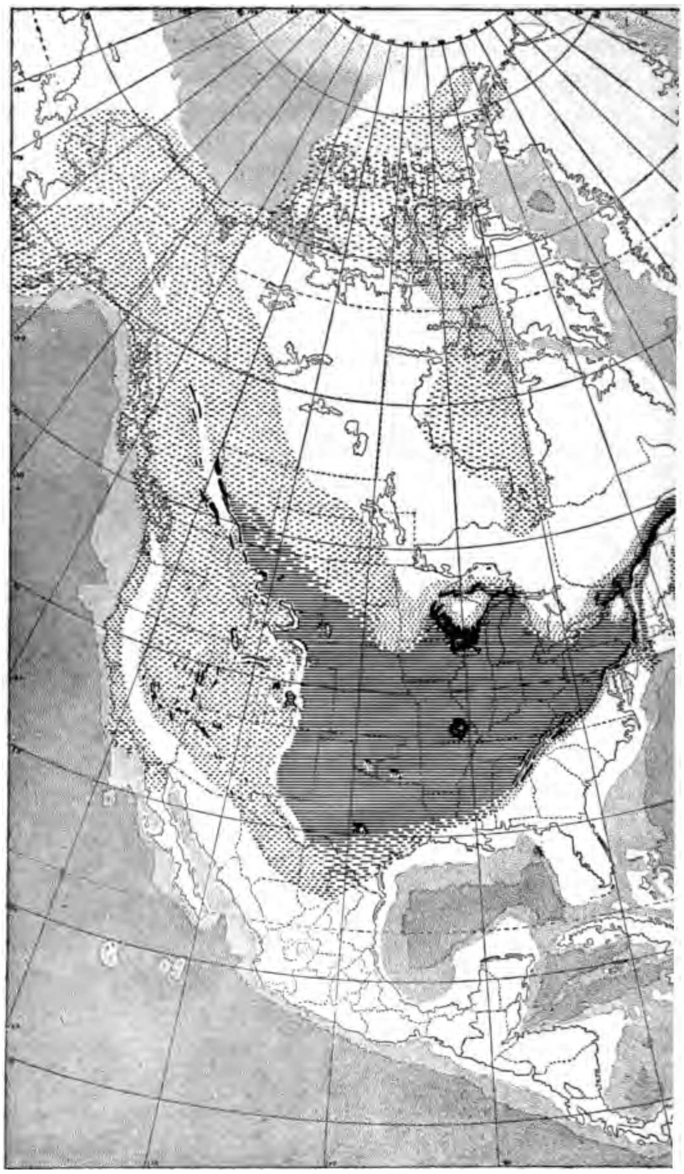

Fig. 95.—Map showing the Upper Cambrian formations. The out
in black. The continuous lines represent areas where the Upper
tions are confidently believed to exist, though concealed. The
areas where there is some reason for believing them to exist.
represent areas from which the Upper Cambrian is believed to ha
by erosion. The unshaded areas have the same meaning as in Fig.

some repetition of what has been said, will help to make clear the method by which the geography (and therefore the geology) of the successive stages of the Cambrian is made out. If, for example, sections 1 and 2 be compared, it is seen that in both cases the three divisions of the Cambrian system are present, and that in both cases the Lower Cambrian rests unconformably on the Proterozoic, while the Middle rests conformably on the Lower, and the Upper on the Middle. From these two sections it is inferred that the Cambrian seas covered the two localities where these sections occur, during at least the later portion of the Early Cambrian, during the Middle Cambrian, and during at least the earlier portion of the Later Cambrian epoch. These sections do not indicate how much of the Upper Cambrian in these two areas has been removed by erosion. From the strict conformity of the three groups of strata, it is probable that the Middle Cambrian beds are present in their full thickness in both sections; that is, that both localities were under water continuously in the Middle Cambrian epoch, and that none of the Middle Cambrian series has been lost by erosion.

It will be noted that the Lower Cambrian in section 1 is much thinner than that in section 2. This might be explained in either of two ways. (1) In the area of section 1, the Proterozoic (Algonkian) surface may have been above water during a part of the Lower Cambrian epoch. If this be true, the land at this point must have sunk so as to let the sea cover it before the close of the epoch. If the area of section 2 was under water longer during the early Cambrian epoch, the greater thickness of the Lower Cambrian in this section would be explained. (2) The other possible explanation of the inequality is found in the unequal rates of accumulation of sediments. So far as the sections show, both areas may have been under water during the whole of the Georgian epoch; but if the rate of sedimentation was slower at 1 than at 2, the thickness of strata would be correspondingly less. From the sections it is not possible to decide between these alternative explanations.

If section 2 be compared with section 3, a somewhat different relation is shown. In the latter, the Lower and Middle Cambrian are both present, while the Upper Cambrian is wanting. This again might be explained in either of two ways. Either eastern Massachusetts rose above sea level after the Middle Cambrian epoch, so that the Upper

Cambrian strata were not deposited there, or the Upp
beds, once deposited, have since been removed by erosi
these alternatives the figure does not decide.

If section 3 be compared with section 4, it will be
latter lacks the Middle Cambrian as well as the Uppe
resting, as before, unconformably on the Proterozoic.
might mean either that the area where it occurs emer
sea before the Middle Cambrian epoch, or that such Midd
Cambrian beds as were once deposited there have since
away by erosion.

From section 7 it is seen that the Lower Cambrian of
York has extraordinary thickness, compared with the
northeast. As in the case of sections 1 and 2, this ma
that the reign of section 7 was under water longer duri
Cambrian epoch, or that sedimentation was here more
rapid rate of accumulation might be accounted for in
way. If the area of section 7 was near a coast, and es
adjoining land was high, rapid sedimentation would be
low. If at the same time the formations of the land were
the rate of sedimentation would be still further incre
may have come into the sea in this vicinity with heavy
ment, or shore currents may have been such as to allow of
rapid accumulation of sediments at this point.

The Upper and Middle Cambrian of section 8 are som
than the corresponding series in sections 1, 2, and 6.
Upper Cambrian is concerned, the thinness might be
moval of its upper part by erosion; but the thinness
Cambrian, taken together with its conformity above and
to indicate that the accumulation of sediment was here
during this epoch. The study of the various sections
made to throw light upon the conditions which existed
where sections are known.

In the areas where sections 1 to 11 and 13 to 17 occ
Cambrian strata are present. This means that the Lo
seas covered these areas. On the other hand, sections
gest, by the absence of the Lower Cambrian formations
did not occupy the areas where these sections occur in th
brian epoch. The only alternative is that the Lower C

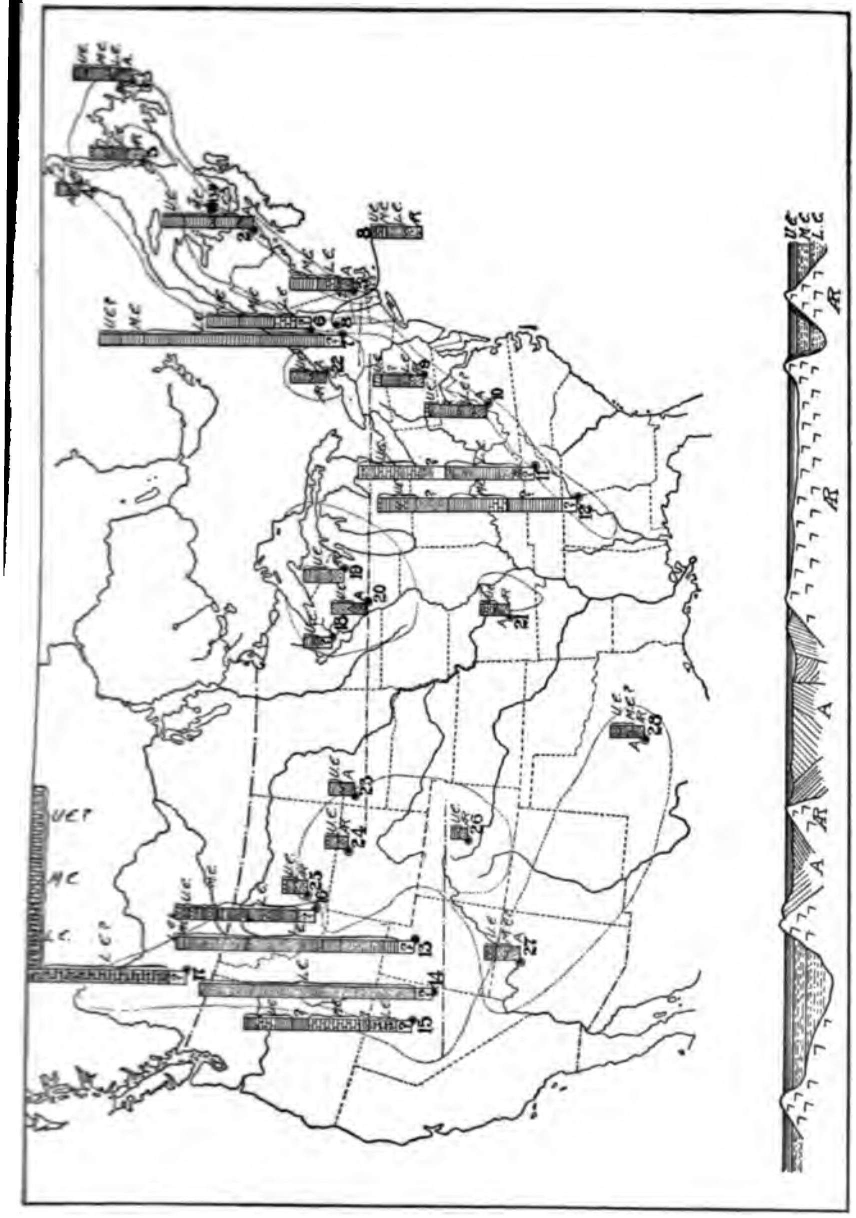

FIG. 96.—A map showing various sections of the Cambrian formations. Æ=Archean, A=Proterozoic (Algonkian), LꞒ=Lower Cambrian, MꞒ=Middle Cambrian, and UꞒ=Upper Cambrian. (After Walcott, U. S. Geol. Surv.)

once covered this area, but were subsequently remov
before the Potsdam epoch, an alternative for which the
be no warrant. Sections 27 and 28 show Middle Cambri
ing on Proterozoic or Archeozoic rock, thus indicating th
Cambrian sea covered the localities of these sections,
Early Cambrian sea did not. Sections 18 to 26 show t
Upper Cambrian beds only, and therefore give some c
extent of the advance of the sea upon the land in the
brian epoch.

Interpretations.

Interpreting these sections, it is inferred that in the
the Cambrian period the sea covered some parts of
border of the present continent as far south as Massac
it occupied a narrow, strait-like belt along the Appal
it was also present in the west, but that the great int
the most part, land (Fig. 90). From the same data it is
during the Middle Cambrian epoch the sea encroached o
from the south and west, reaching western Montana,
Texas during the Middle Cambrian epoch (Fig. 96). S
the Potsdam (Saratogan) epoch, the sea gained domini
land until, at its close, a large part of the area of the
was beneath the sea (Fig. 96).

Theoretically, this result may have been brought ab
of the sea, or by a lowering of the land, or by both togethe
ing the point of view somewhat, it may have been brou
a deep-seated deformation of the earth's body, or by superf
whether gradational or deformational, or by both combi
not be best to try to reach final conclusions where the
intricate and the data so imperfect as in this case, but
weigh the considerations that favor one or another of
participating agencies and to try to discriminate betwe
of the inevitable agencies and that of the more or less unc

There is need to discriminate at the outset between t
deformation. The one is that which has just been calle
mation, whose origin is presumed to be internal, while the
will be defined below, is *superficial deformation,* and more

pendent of internal forces at the time of its accomplishment.[1] As will appear presently, *superficial deformations* are not excluded by the general evidence against profound deformations. In the present case we may first inquire how far gradation and allied agencies may have been effective in bringing about the transgression of the sea over a large part of the American continent in the later part of the Cambrian period. We may inquire next how far superficial deformations may have coöperated with gradation in bringing about the transgression of the sea; and then, if these seem inadequate, we may resort to the more hypothetical forces that reside in the deeper body of the earth.

(1) **How far may gradation have been competent to bring about the submergence of the continent?**—Gradation is perpetual and inevitable where land and sea exist. The waves attack the land along its borders, and the familiar agents of degradation reduce its surface. The former is a direct cause of the encroachment of the sea upon the land, and the latter an indirect one, since all sediments transported from the land and deposited beneath the sea displace an equal volume of water, and correspondingly raise the sea surface. Small as this rise must have been for any brief period, its effect was to cause the sea to advance upon the land. The lowering of the land by degradation at the same time, facilitated the advance. *If continued long enough,* this coöperative process of shore-cutting around the borders of the lands, of down-cutting over the whole surface, and of uplifting of sea-level, must inevitably have caused the water to cover the whole continent and to spread deposits over all but the last remnants of it, *provided there was no deformation of the body of the earth in the meantime.* This familiar process is illustrated in miniature in Vol. I, pp. 60–62, where the lifting of the sea-level is neglected, because infinitesimal in that case. Since this complex process is inevitable, it is well to assign to it whatever it is competent to do consistently with the results of other agencies known to have been in operation at the same time.

It has been computed that if the earth, in its present condition, were to remain without deformation for the requisite period, the erosion of the continents and the transfer of the material to the sea would raise the sea-level about 650 feet (Vol. I, p. 545). The last remnants of the

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[1] For the general treatment of these two phases of deformation, see Vol. I, pp. 548–580, and this Vol., pp. 119–132.

continents to be submerged by this process would, ther
that height above the present sea-level. The disturbe
the Proterozoic formations, and the truncated conditio
turned beds, may be taken as good evidence that the co
forth from the sea rather prominently at the close of t
era. The actual mass of the continents is not known, an
essential for present purposes. The higher the contine
the material available for removal to the sea and so for th
surface when deposited beneath it, and the more the
to submerge the continents; while the lower the continen
material available for lifting the sea, and the less lifting n
it to cover the land. It is a case of reciprocal relations
accommodation, in any event. The result is certain i
the time be long enough and *deformation does not inte*
mation is a possible bar, as well as a possible aid, to the
of the sea on the land. A satisfactory explanation of t
great tracts of land by the sea may therefore require th
the limitation, of profound crustal movements, rath
participation.

The direct evidence of gradation in the Cambrian
and firm, for there is no ground to doubt that the mai
Cambrian sediments was eroded from the land and de
sea. This gradation tended to lower the land and raise
are safe, therefore, in concluding that surface action wa
in the result attained. There is much evidence tha
progress was made toward the base-leveling of the A
nent, and of other continents as well, before the close of
period. The very fact of the spreading of the sea so w
interior of a continent, and of the laying down of a rela
and not very thick formation of sandstone over such b
a surface which approached a plane, though underlain
are commonly much deformed, is in itself evidence of e
ing by degradation.

Now base-leveling *implies a nearly undisturbed attit*
and sea during its progress, and hence in itself favors th
great deformation affected the continent while it was
harmony with this view, there is an absence of direct
profound deformation during the Cambrian period. T

fore a presumption in favor of gradation and against body deformation during the period, and good practice in interpretation leads us to inquire how far the former may have been the cause of the submergence of the continent, before we resort to the doubtful expedient of invoking profound deformation.

If gradation were the *sole* agency involved in the submergence of the lands, the advance of the sea should have been systematic, though not necessarily equal in rate or extent at all times and places, and along this line a means may be found of judging how far this agency was a real one. Without attempting to make a full application of this test here, it seems certain that there were some shiftings of the areas of deposition other than those which might have arisen from a simple gradational advance of the sea upon the land, and that there are specific evidences of warping, as implied by the differences in the depth of the deposits and in their characters and relations to one another, as brought out in the previous descriptions. None of these warpings were, however, of the more intense and declared type, such as occurred repeatedly in the Proterozoic and Archeozoic eras. Those which are now known were of a relatively gentle type, and limited in amount and in prevalence. These characteristics of the Cambrian deformations lead to inquiry under the second head.

(2) **How far may superficial deformation have contributed to the submergence of the lands?**—(*a*) *Lateral spreading.*—The continental platforms now stand forth above the ocean bottom as great plateaus. They may be roundly estimated to rise 15,000 feet above their true sub-oceanic base. Their weight develops a pressure on their basal parts that may safely be estimated at 15,000 to 20,000 pounds to the square inch.[1] This pressure *tends to cause the platforms to spread by lateral creeping.* This is opposed by the strength of the rock, and by the hydrostatic pressure of the oceans against the sides of the platforms. If this last be estimated at 5000 pounds per square inch at the bottom, there remains an unbalanced pressure of 10,000 to 15,000 pounds per square inch. Even the lesser of these figures is equal to

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[1] For rough computations where exact accuracy is immaterial, it is convenient to remember that a cubic foot of rock weighs about as many pounds as there are square inches in its base, though usually somewhat more. Hoskins, in his computation of the strength of domes (Vol. I, p. 581), takes 180 pounds as the weight of a cubic foot of firm crystalline rock of the granitic type. 180 ÷ 144 = 1.25. At 2.7 sp. gr., a cubic foot weighs 167 lbs. 167 ÷ 144 = 1.16.

the crushing strength of some of the weaker rocks, an
percentage of the crushing strength of even the strongest
less pressure than this, rocks are often observed to cree
and canyons. It is not improbable, therefore, that a p
magnitude, constantly exerted for a prolonged period,
some spreading of the great continental platforms, and h
lowering of their surfaces, and (2) at the same time so
sea-level.

Such a force, perpetually in readiness to act, if not ac
ing movement, would always coöperate with any othe
tended to work in the same direction, or to develop w
resisting power of the continental mass. Coöperating wi
lar changes concerned in rock alteration, this pressure
give the rocks lateral extension in the line of least resista
it is really very effective or not, it is at least a constant
to produce lateral creep, and hence to cause a lowering
of the continents, a rise of the surface of the sea, and ther
ing of the ocean waters.

We have considered this point on the basis of the p
heights of the continents above the ocean floor. A lit
tion will show that we are not likely to be far in error in
lar figures to the Cambrian continents, for if the volum
was then not far from what it is to-day, the ocean basi
had much the same capacity as now, and as the conti
appear to have had much the same area as they now h
in Cambrian times may be assumed to have been of the
order of magnitude as now. It may at least be assumed
sufficiently great to have involved these consideration
seen that continental spreading or creeping will, within
its operation, diminish the capacity of the ocean basins
to cause the waters to overflow the lands.

No attempt is here made to definitely estimate the
this agency, but some considerations which bear upon it
(1′) It cannot, probably, have been of a very high orde
have affected adversely the perpetuation of the continent
degree than the record indicates. If the continental
spread with anything like the facility that continental i
the land would probably have been completely subme

each of the great periods of body deformation. It is believed that during great deformations the land segments are squeezed between the ocean segments, and forced up relatively (Vol. I, pp. 542–551), and that the perpetuation of the continents in the face of gradation, spreading, etc., is dependent on this periodic rejuvenation. As the periods between these rejuvenations of the continents appear to have been long, the lateral creeping action must have been slow and limited in amount relatively; yet it may have counted for something in the lowering of the surface, and in the spread of the sea. (2′) The *faulting* of the land areas is predominantly of the tensional type, and this type is hence called *normal*. Just how this type of faulting came to be a dominant one, is an outstanding problem of geology. It may have taken place in part during the periods of continental compression; but the thrust (reversed) faulting is most reasonably referred to these periods, and it is not easy to see how tension faulting could have predominated during a period of dominant lateral thrust. If tension faults did not occur abundantly during periods of compression, they are chiefly to be referred to the intervening periods of quiescence or relaxation, and the spreading of the continents would seem to furnish appropriate conditions. Normal faulting may therefore finally prove to be an evidence of a glacier-like, but extremely slow, creep of the continental masses. (3′) The upper portion of all formations composed of non-plastic rocks is affected by crevices, and these manifest a nearly universal tendency to gap. Taken altogether, the amount of gaping thus indicated is very considerable, even when allowance is made for enlargement by solution or any demonstrable shrinkage. Cracking and spreading of this kind is what might be expected if the deeper parts have crept laterally under pressure, just as similar cracks open and widen on the surface of asphalt when it slowly spreads under its own weight. Without affirming that this is the explanation of crevicing, or that it is evidence of continental spreading, the mutual fitness of the two is worthy of consideration.

(*b*) **Mutual adjustment of continental and oceanic segments.**—Continental spreading would be operative, as seen above, even if the base plane on which the continent may be conceived to rest were absolutely inflexible. This, however, is not the case, and there is need now to consider whether the continents might not sink and cause the ocean bottoms to rise by reciprocal action, like the two arms of a balance.

If the continental segments, taken as deep masses, weigh
the equivalent portions of the sub-oceanic segments, the
tended to settle down and force the latter up until they r
static equilibrium. This would of course be opposed b
of the rock, as in the previous case. If the continental
a lower specific gravity than the oceanic segments, so that
in essential balance, there would have been no tendency
to sink, though the tendency to spread, as discussed abo
remain.

Pendulum observations seem to show that, on the w
tinental segments are now in approximate hydrostati
with the oceanic segments, and on this is built the doctr
or the essentially balanced condition of the earth's c
standing the inequalities of its height.[1] At the same ti
observations seem to show that notably elevated regions,
that of the Cordilleran tract, stand higher than they
were in isostatic balance.[2] There is in such evidences
considerations that cannot be stated with sufficient b
place, ground for thinking that during profound bodil
the continental segments may be pressed up, in por
beyond the plane of equilibrium, and that during the
escence that follows, they tend to settle back to the eq

If this view be well taken, there is ground for belie
portions of the Cambrian continents were pressed up be
of isostatic equilibrium during the late Proterozoic def
that they slowly subsided during the long Cambrian
nature of the case, such a movement would be unsyn
tributed, and the result would be manifested in slow,
It would be more efficient in the early stages of the q
than later, for erosion would join with the subsidence
overweighting.

(*c*) **Isostatic adjustments due to gradation.**—If the con
in isostatic equilibrium at the opening of the Cambrian

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[1] Dutton, Greater Problems of Physical Geology, Bull. Phil.
XI; also Am. Jour. Sci., III, 1874; Woodward, Mathematical The
Vice-Pres. Address, Math. Sect. Am. Assoc. Adv. Sci., 1899; also
for 1890.

[2] Putnam and Gilbert, Bull. Phil. Soc. Washington, Vol. XI
Gilbert, Jour. of Geol., Vol. III, p. 331.

moval of matter from the protruding surfaces, and its deposition about the borders of the land, would have disturbed the balance and caused some tendency to warping; for even if the body of the earth be too rigid to be sensibly influenced by such changes, the local loading, where deep deposits were made, would somewhat compress the rock beneath, and the unloading, where the surface was cut away, would permit their expansion. Such effects would obviously be limited if the crust is inflexible to such moderate stresses; but the crust is sometimes held to be responsive to very moderate loading and unloading. The general result of changes of level brought about by this cause would, on the whole, be opposed to submergence of the land.

(*d*) **Adjustments due to thermal changes resulting from gradation.**—The unequal erosion and deposition of the period tended to unequal loss of heat, and hence to unequal contraction, and so contributed slightly to superficial warping. The general effects of changes brought about in this way would have been opposed to those brought about by isostatic adjustments due to gradation.

(*e*) **Adjustments due to thermal changes incident to diastrophism.**—In the course of the distortion of the crust attending a great period of diastrophism, such as that which preceded the Cambrian period, unequal temperatures were undoubtedly developed in the compressed, contorted, and disrupted masses, and these tended to equalize themselves by distribution during the following period of quiescence, and this doubtless resulted in some gentle warping. This may have been a contributing cause to submergence.

(*f*) **Adjustments due to easing of stresses.**—So, too, in the process of distortion, unequal stresses must certainly have been developed, and these would tend to ease themselves by slow changes as time went on, and this also contributed to mild warpings and slight deformations. The general tendency of such changes was probably toward a lowering of the elevated segments of the earth.

Without attempting to make the list entirely exhaustive, it may be remarked that here is a group of changes which had their origin, for the greater part, *in previous diastrophism*, and which probably continued to slightly modify the configuration of the surface for a long time after the main diastrophic action had ceased. They may have coöperated with the gradational process through the Cambrian period. They may have interfered with the base-leveling process in some measure, and may have notably modified it locally; but, on the who they aided in lowering the continents, they assisted in t transgression of the sea, the great fact to be explained.

If these agencies are adequate, it is unnecessary to ap more occult and periodic forces that affect the profounde tions of the earth. More particularly is this true because, noted in passing, the usual effects of these profounder agen the opposite character. Their normal work appears to be the ocean basins, to withdraw the epicontinental seas, t the continents laterally, and to increase their protuberances.

The general tenor of these considerations, taken in conn the sedimentary record of the period, favors the view tha beginning to the close of the Cambrian, there was general so far as the profounder phases of bodily deformation were and that gradation (degradation of the land, and aggrada sea bottom) was a principal cause of the transgression of t that the transgression thus brought about was attended a by superficial warpings and deformations. These deforma for the most part, of the milder kind, and due to a series o adjustments springing largely from previous diastrophis with incidental causes of a superficial nature. Locally, th have been somewhat pronounced, as indicated by the great nesses of the Cambrian sediments, but as will be seen later common interpretation of these great thicknesses may be question, at least to the extent of notably reducing the deformations which they have been assumed to imply.

The base-leveling movement, attended by further se sion, continued to be the dominant feature of the earlier po next period.

Basis for the Subdivision of the Cambrian.

We have now to inquire the means by which the Cam may be recognized, and further the means by which the I brian may be distinguished from the Middle, and the Midd Upper. In other words, how is it known that the strat sections 18–26, of Fig. 96, are Cambrian, and how is it know are Upper Cambrian, as distinct from Lower and Middle.

Stratigraphic relations.—From what has gone before, i that the stratigraphic relations of a formation with the formations next beneath do not necessarily determine its age. As the sections show, the Lower, the Middle, and the Upper Cambrian strata in turn rest unconformably upon pre-Cambrian rocks. Just as the Upper Cambrian overlaps the earlier formations of the period, resting unconformably on the pre-Cambrian, so any later formation might overlap the Upper Cambrian and sustain similar relations to the Proterozoic and Archean systems. It follows that where one formation is unconformable on another of known age, the stratigraphic relations between them do not determine the age of the younger, beyond the general fact that it is younger than the base on which it rests. If, on the other hand, a formation is conformable on another of known age, the presumption is strong that the upper succeeded the lower without interruption. If this inference be correct, the approximate age of the upper is known. But even here there is possibility of error. If, after a formation is deposited, the sea bottom where it lies is brought above water level without deformation of the beds, and if the elevation be so slight as not to permit of much subaërial erosion on the newly emerged surface, it might be submerged at a later time and receive a new series of deposits, the beds of which would be stratigraphically conformable, or approximately so, with those below. It is clear, therefore, that the answer to the question proposed in this paragraph is not always to be found in the stratigraphy of the formations concerned. The complete answer involves as well a consideration of the fossils which the formations contain.

Fossils.—It has been stated that life existed in the preceding eras. Yet in the Proterozoic formations, fossils are exceedingly rare, though it does not follow that life was sparse during their deposition. When, after the lapse of the long interval between the deposition of the youngest Proterozoic and the oldest Cambrian strata, as known in most parts of North America where detailed geological work has been done, the waters again advanced over the land surface, making the deposits which are now known as Cambrian, they teemed with life. As the sediments were deposited, the shells or such other hard parts as the animals possessed, were buried in the gathering sands and muds, and some of them, or the impressions which they made, remain to this day. The Cambrian is therefore the oldest known system of rocks which contains abundant fossils.

The fossils in the strata of any division of the Cambri
the known fauna of that stage. The fossils found prol
represent the full fauna of any stage, since it is hardly tc
that relics of all species have been preserved. The term fε
a geographic and a geologic significance. The Upper Ca
includes all forms of animal life of the Upper Cambrian
the Upper Cambrian fauna of New York includes only thos
lived in that region at that time.

With the possible exception of the Atlantic coast re
Newfoundland, the oldest known part of the Cambrian sy
certain fossils which are distinctive. Among them are tl
genus of trilobites known as *Olenellus* (Fig. 118 *a*, p. 281)
the representatives of the genus Olenellus, there are many
of various types of life. To the aggregate, the name *Ol*
has been given. It is not to be understood that represe
genus Olenellus itself are found at all points where the
the Cambrian system is present, or that other genera of
absent. Wherever Olenelli are found, various species o
of trilobites occur, as well as various species of genera o
of animals, and wherever these other species of the Olen
found, the Olenelli themselves may be expected. G
very generally agreed to regard the base of the formati
the Olenellus fauna as the base of the Cambrian syste
nition of the base of the system has been found appl
America and Europe, and in both continents the Ole
the oldest known abundant fauna. Conformable b
below the Olenellus horizon, and whose character gives
they were deposited immediately preceding the Olene
under the same general conditions, are better classe
than as Proterozoic, and they may be tentatively referr
brian.

As time went on, the inhabitants of the sea change
Cambrian formations represent a sufficiently long int
the fossils in the lower beds are not altogether like those
single plane is there, as a rule, a very notable change

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[1] For a general discussion of the Olenellus fauna, see Walcott, '
U. S. Geol. Surv.

[2] Walcott, Bull. 81, U. S. Geol. Surv.

in successively higher beds some of the species found below disappear, and new species come in, as if to take their places.

Where the full system of the Cambrian is presented, the Olenellus fauna is found to be restricted to its lower portion. So strictly is this true, that (with the possible exception of Newfoundland, see p. 245) the rocks containing the Olenellus fauna are regarded as constituting the Lower Cambrian. *Olenellus Cambrian* therefore becomes synonomous with *Lower Cambrian* and with *Georgian.*

At about that stage in the Cambrian system where the genus Olenellus drops out, the genus *Paradoxides* appears; this is at least true for Newfoundland and Europe. The other species of fossils associated with the genus Paradoxides are somewhat different from those associated with the genus Olenellus, and many of them have a wider range than the Paradoxides. The Paradoxides and its associates constitute the *Paradoxides fauna,* a fauna which includes many species of other genera of trilobites, and many species of other classes of animals not related to trilobites. By general agreement, the Middle Cambrian of the regions specified is defined by the Paradoxides fauna, so that *Paradoxides Cambrian, Middle Cambrian,* and *Acadian* are synonomous terms. The Paradoxides fauna is so unlike the Olenellus fauna that the two may be distinguished by those familiar with fossils. In the western part of North America, the Middle Cambrian series does not contain fossils of the genus Paradoxides, but its fauna is none the less distinct from that of the Lower Cambrian series.

In like manner the Paradoxides (or other Middle Cambrian fauna) is succeeded by another, known as the *Olenus* or *Dikellocephalus fauna,* and this fauna characterizes the series of strata which overlie the Middle Cambrian. Geologists have agreed to define the Upper Cambrian as the series of strata carrying the Olenus or Dikellocephalus fauna. This definition is found to be applicable to Europe as well as to America.

It is not to be understood that every species of the Paradoxides or other Middle Cambrian fauna is unlike every species of the Olenellus fauna below and the Olenus fauna above. This is by no means true; but so many of the forms of the three faunas are different, that with a considerable number of species to judge from, their separation is possible.

In the discrimination of any of these faunas an analogy with living animals is suggested. The present faunas of North and South

America are reasonably distinct; but it does not follow 1 no species in common. Given a single animal, even an not be able to say that it was from the one continent or fi though with certain species even this might be done; number of animals from either continent were availabl possible to determine to which continent, that is, to wh *fauna*, they belonged. So with the several Cambrian have some species in common, and the common specie to distinguish them, or the groups of strata which conta one another. But certain species are found only in the other species only in the Middle, and still others only in t of the system, and these species serve to distinguish the sions. If but few fossils are present, and these not of d the several members of the system may not be separ another on paleontological grounds. Once the succes is established—Olenellus below, Paradoxides in the mid locephalus above—it is customary to refer all rocks whi Olenellus fauna to the Lower Cambrian, all which con doxides fauna to the Middle Cambrian, and all which cont or Dikellocephalus fauna to the Upper Cambrian.

Sequence of faunas based on stratigraphy.—It is no stood that rocks which contain such faunas are classed t because they contain certain fossils. This is not the p least not the only or the fundamental principle, which be grouped together. The order of sequence of faunas is f by the superposition of the strata. The Olenellus faun known to be older than the Paradoxides fauna, if the b the former were not known to underlie beds containing is likewise because of their superposition that the rocks Upper Cambrian fauna are known to be younger than t the Middle Cambrian fauna; in other words, *the basis fo means of fossils must necessarily be stratigraphic.*

Once the succession of faunas is established, the fo most important aid in correlation, and frequently afford for it. It should be remembered, however, that the cl of different regions together under the name of Lower Ca not primarily that they contain the same fossils, but believed to have been deposited at about the same time succession of faunas in different regions is believed to be in a general way the same, likeness of fossils in the formations of different regions is thought to be evidence of their approximate contemporaneity. Fossils, therefore, are but a means to an end, so far as the correlation of strata is concerned. It is not to be inferred, however, that the Olenellus fauna ceased to exist at exactly the same time in different regions of the same continent, much less in different continents, and the variations from a true chronological classification which the correlation by fossils involves cannot be avoided.

Upper limit of the Cambrian system.—Not only have the three principal faunal stages of the Cambrian been agreed upon, but it has been further agreed to draw the division line between the Cambrian system and that which overlies it at the horizon where the Olenus fauna ends. The upper limit of the Olenus fauna is therefore the upper limit of the Cambrian system, and corresponds in time with the end of the Cambrian period.

At first thought this division may seem arbitrary, but in reality it is not without a natural basis. The Upper Cambrian formations are occasionally unconformable beneath the next succeeding ones, and in such places the division is a natural one. Much more commonly, the next system is conformable with the Upper Cambrian; but even in conformable series, the faunal changes are more rapid in some parts than in others, and the horizon where the Olenus fauna ends is one where these changes are relatively abrupt. The horizons of rapid change in the character of the fossils may represent times of geographic changes, from which changes in sedimentation and life resulted. Throughout geological history great faunal changes have followed changes in the relations of land and sea.

Fig. 97 will help to make clear the principles here set forth. The vertical space of the diagram may be taken to represent the Cambrian system, and a part of the system next above. The fauna found at the bottom, *a*, undergoes gradual change in the overlying beds up to the horizon *b*. In the beds next following, *b* to *c*, the faunal changes are more rapid, and these beds represent the transition from the Lower to the Middle Cambrian. From *c* to *d* the Middle Cambrian fauna is found, though undergoing gradual change with successive beds. Between *d* and *e* the changes in the fossils are again more marked, and these beds represent the transition from the Middle Cambrian to the

Upper. From *e* to *f* the Upper Cambrian fauna is four
f and *g* the faunal changes are again more rapid and m
than between *b* and *c*, or *d* and *e*. Since the changes at
are greater than at the other corresponding horizons belo
above and below *fg* are referred, not to different epochs

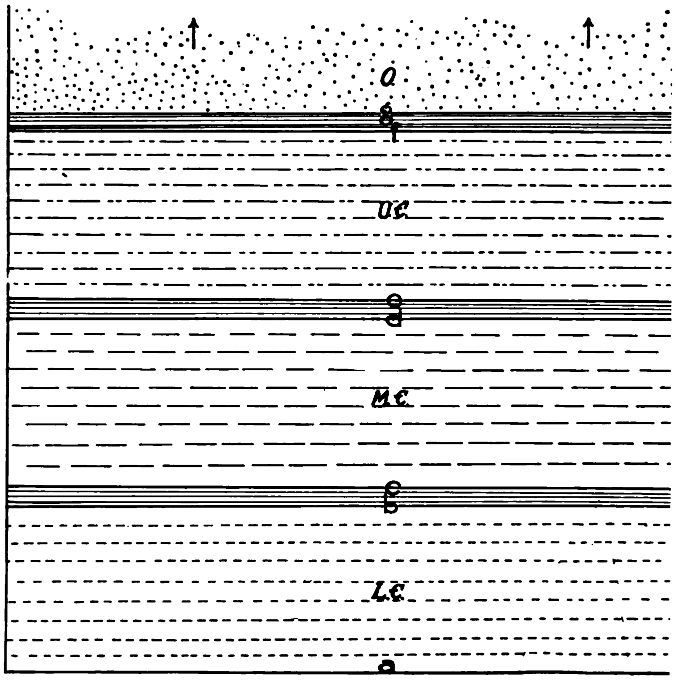

FIG. 97.—Diagram to illustrate classification based on unequally rapi faunas. The fossils of the strata, *bc*, *de*, and *fg* record more rapid than the strata *ab*, *cd*, and *ef*. *bc* represents the transition from L to Middle Cambrian; *dc* from the Middle Cambrian to the Upper C from the Upper Cambrian to the Ordovician. *ab*, *cd*, and *ef* re Middle, and Upper Cambrian respectively.

period, but to different periods. The beds between *f* an
represent the transition from the Upper Cambrian to the
ing, or Ordovician fauna.

A few years since, question was raised concerning the accu
plicity of the interpretation[1] of the Cambrian sketched above. O
tions concerned the equivalence of the so-called Olenellus fauna of
and Europe, and those of the Hudson-Champlain valley and th

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[1] Matthew, Am. Geol., Vol. XIX, 1897, p. 395.

of North America. The Olenelli of Newfoundland and Europe were thought to be so different from the Olenelli of most of North America (see Fig. 118, p. 281) as to be more properly referred to another genus (Holmia), and the Holmia fauna, as a whole, was thought to be simpler than the Olenellus fauna, and therefore perhaps older. Furthermore, the distinct Paradoxides fauna is found only in those regions where the Holmia fauna occurs; it is not in immediate association with the commoner types of Olenellus. The stratigraphic relations of the types of Olenellus and Paradoxides faunas therefore is not established, *if the Holmia and Olenellus faunas be not one.* Question has also been raised as to the contemporaneity of the Middle Cambrian fauna of the larger part of North America, and the Paradoxides fauna of Europe.

In the Hudson-Champlain valley the Olenellus fauna appears to have lived on until the advent of the Dikellocephalus fauna. No well-marked Middle Cambrian fauna intervenes, though sedimentation seems to have been uninterrupted.

The questions which have been raised may lead to some minor modification of former views, but do not seem likely to change them fundamentally, or to lead to very different opinion concerning the course of the physical history of the continent in the Cambrian period. They seem to make two interpretations possible. The one is that the Holmia fauna of Europe and Newfoundland was contemporaneous with the Olenellus fauna of North America. According to this view, they are one geologically (chronologically), but somewhat distinct geographically. In this case it would not be strange that the succeeding faunas were also somewhat unlike, the Paradoxides fauna succeeding the Holmia in one region, and the Middle Cambrian, without the genus Paradoxides, succeeding the Olenellus fauna elsewhere. The geographic diversity may have been as great in the Middle as in the Early Cambrian. According to this view, the Olenellus fauna of the Hudson-Champlain valley may have been contemporaneous with both the Holmia and the Paradoxides fauna of the region farther east. A Holmia has been found in Pennsylvania, but a partial barrier between Newfoundland and the Hudson-Champlain valley, is supposed to have prevented free mingling of the contemporaneous Holmia and Olenellus faunas. It must be further supposed that the causes which brought about a change from the Early to the Middle Cambrian faunas, both to the east and to the west, did not produce like results in the Champlain valley, since the Lower Cambrian (Olenellus) fauna lived on. None of these assumptions are in violation of principles which are believed to have been in operation throughout geological history.

The alternative interpretation is that the Holmia fauna is really older than the Olenellus proper, and that the Olenellus of the west and of the Hudson-Champlain valley may have been contemporaneous with the Paradoxides of the east. According to this interpretation, the Paradoxides fauna of Newfoundland may have been contemporaneous, at least in part, with the Olenellus fauna of New York and with the Olenellus and Middle Cambrian faunas of the west. Like the last, this interpretation does not violate known principles of life development, for two distinct faunas in one region may have been contemporaneous with one fauna elsewhere, where the causes of biological change w less. Between these interpretations, the former now seems the mor

Sedimentation in the Cambrian Period.

Sedimentation in the Cambrian period appears to hav the general laws that govern deposition in periods of co freedom from great deforming movements, and hence of p base-leveling. While at all stages there was doubtless som lation of sediment on land-areas and in land-waters, the mentation was in the sea, and the area of sedimentation may b as corresponding approximately to the area of the sea. I the rate of sedimentation was probably faster in the early the period when the land-area was largest and probably hig slower in the later stages after the land surface had been l erosion, and narrowed by the encroachment of the sea. Geog the rate was probably more rapid near the land, and less rap from the shores in deeper water, in accordance with general possible exceptions to this are to be recognized at those sta very extensive and shallow epicontinental seas had been by gradational processes, continental spreading, etc., for in deposition far from shore perhaps kept close pace with that n and may even in some cases have exceeded it.

Sources and kinds of sediments.—As in other geologi the land-derived sediments came from the various format exposed to erosion, the larger part from those which were u the most rapid degradation. The sediments gathered alon mediate borders of the land were generally different from th deposited farther out at sea, but this difference was less n broad shallow epicontinental seas were developed, for in the conditions were more nearly equal over wide areas. Th in the abysmal depths of the ocean were of course notably from those of the terrigenous belt, but none of the former are be now exposed. Even along shore there were considerable v both because of variations in the character of the formati rise to the sediments, and because of the differences in wa and current action.

The Cambrian formations include all common phases of se rocks. There are conglomerates, presumably accumulated shores of the time; there are sandstones, the sand of which was deposited in shallow water where the waves were sufficiently vigorous to keep the mud from settling; shales representing the deposits made in stiller or deeper water; and beds of limestone representing, for the most part, the accumulations of shells, etc., in regions to which terrigenous sediments were not carried in quantity. On the whole, the proportion of limestone is greater in the upper part of the system than in the lower, and toward the south and southeast, rather than in other regions.

Geographic variations in the sediments.—The distribution of these various sorts of sedimentary rocks, shows that various kinds of detrital beds were accumulating in different places at the same time, and at the same place at different times. Thus in the vicinity of Quebec, the Cambrian system is represented by 5000 to 6000 feet of shale. Between the Adirondack and the Green mountains there are 3000 to 5000 feet of shale overlying 1000 feet of limestone, and some of the limestone appears to be the time-equivalent of some of the shale of Quebec. In Washington County, N. Y., the Cambrian strata are 10,000 or 12,000 feet thick, the upper and greater portion being of slate (formerly shale) and sandstone, while the lower and thinner part (1400 feet) is limestone. Farther south, the system is composed chiefly of shale (or slate) and sandstone (or quartzite). In Tennessee and North Carolina there are great thicknesses of quartzite overlain by shales. In Georgia and Alabama, the thickness of the system is something like 10,000 feet, the strata being made up of shale and sandstone with some limestone.

In the southern part of the Appalachian region, the general order of deposition was sandstone, followed by shale, and that by a small amount of limestone. In Virginia, where the system is 3400 feet thick, it is chiefly made up of shale, which runs down well toward its base. North of Virginia, as far as New York and Vermont, there seems to have been a great variety of sediment, including many beds of limestone near the base of the system. Since throughout most of the Appalachian belt, all divisions of the Cambrian are represented, it is evident from the above statements that while limestone was forming in one region, sandstone and shale were forming in others, and *vice versa*. If the sequence of beds in the Appalachian region be compared with that in other regions, they are found to vary widely. Thus the Upper Cambrian

of the interior is mainly sandstone, while that of the sou
lachians is shale and limestone. Similar variations are
everywhere. They are indeed so prevalent that there is
reason for assuming that the Upper Cambrian of one regi
sented by sandstone, because that is the formation of the cc
time elsewhere.

Not only were beds of sediment of different sorts
at the same time in different places, but they were accumu
different rates, as suggested by the sections in Fig. 96.
borne in mind persistently in the study of all stratified
that equal thicknesses of rock do not necessarily accumul
periods of time. The full section of the Middle Cambrian
that was deposited during the whole of the Middle Cam
seems to be present at many points, yet the thickness o
Cambrian strata is far from uniform.

The Lower and Middle Cambrian sediments of the
belt appear to have been deposited in a narrow interior se
which lay between the pre-Cambrian rocks just east of
mountains and the great interior land area to the west (F
beds accumulated in this narrow interior sea are such a
that the water was shallow, in spite of the fact that the
estimated to have a thickness of several thousand feet.
contradiction may be the result of an exaggerated estimate
or, if the estimated thicknesses are correct, it may be
supposing that, as the sediments were laid down in the s
the bed on which they gathered sank about as rapidly as
lated, so that the whole series, from bottom to top, was
shallow water; or the beds may have been built out fr
in sloping attitudes, their upper parts being always in s
In the later part of the Cambrian period, the narrow Ap
of the earlier epochs had become a part of the wider
which covered much of North America, but the wa
shallow.

The Cambrian formations along the North Atlanti
England and north) are such as to indicate that the sedin
lated near shore and in shallow water, that during their
there were frequent oscillations of level, but that, on t
sea gradually gained on the land. The distribution of

in this region indicates that the deposits were made, in many cases, in narrow arms of the sea, surrounded, or nearly surrounded, by high lands composed of older formations. Limestone is, however, not altogether wanting (Fig. 98). The fossils of this region indicate that a land barrier existed to the east, in the region which is now covered with water, shutting off the region where the known strata accumulated from free connection with the open sea in this direction. They are also thought to indicate that the waters in which the sediments of this region accumulated were not in free communication with those in which the sediments of the Appalachian region were laid down.

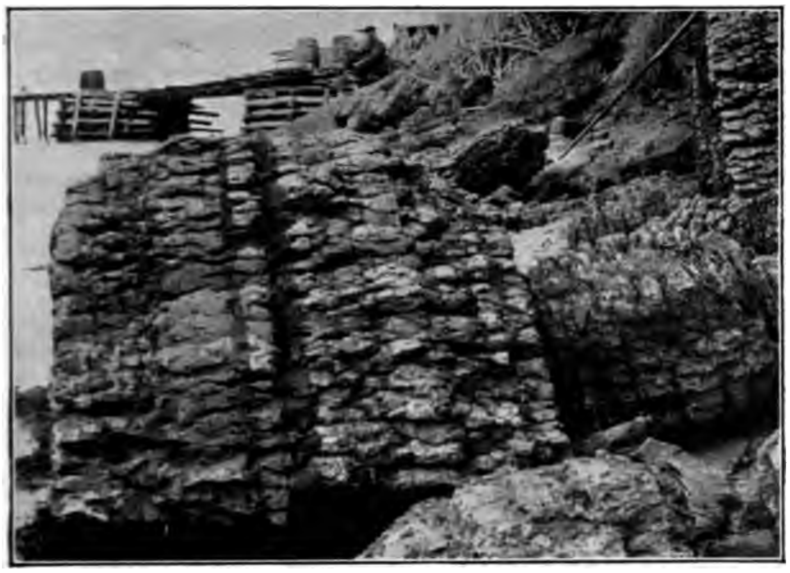

FIG. 98.—Nodular limestone, Lower Cambrian, from the east side of Smith Point, Smith Sound, Trinity Bay, Newfoundland. (Walcott, U. S. Geol. Surv.)

The fact that in the northern interior of the United States the Upper Cambrian formation is generally of sandstone, and that this sandstone is wide-spread, indicates that the water was so shallow during its deposition that the waves were competent to transport sand for long distances. Furthermore, the structure of the strata, with their cross-bedding (Fig. 99) and ripple marks, shows that the whole series, so far as seen, was deposited in shallow water, and therefore on a base which was gradually submerged as the sediments were accumulated.

In other words, the structure of the formation confirms the
drawn from the distribution of the Upper Cambrian, th
deposited in an advancing sea.

The greater portion of limestone, chiefly dolomite, in t
Cambrian series of the southern and southeastern interior,
clearer seas, but not necessarily to deep ones. The adja
were perhaps too low to yield abundant sediment. It has

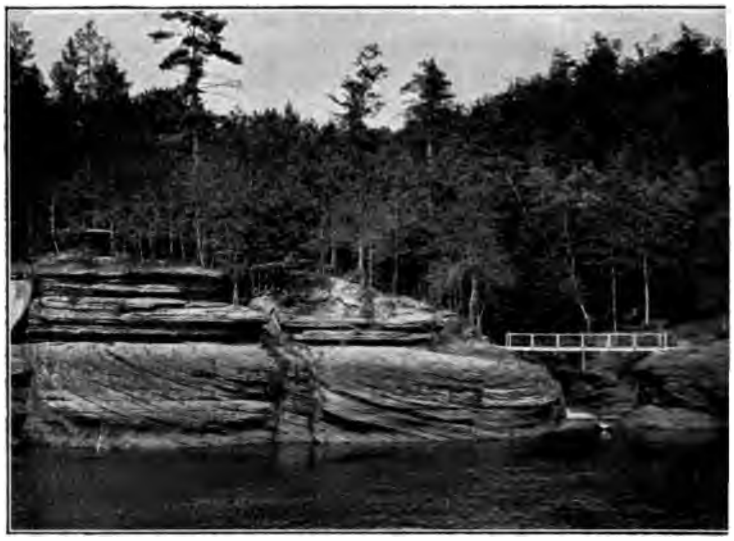

Fig. 99.—Cross-bedded Potsdam sandstone, Dells of the Wisconsin. (B

jectured, but not proved, that the limestone of the interior w
precipitated from solution.[1] Limestone is also an importa
the Upper Cambrian of the Rocky Mountains,[2] though cla
predominate farther west. Where the Upper Cambrian is
it is not usually sharply differentiated from the overlying O
This is the case in the southern Appalachians,[3] as well as
Territory, Missouri,[4] and Nevada.[5]

Variation in a given locality.—The variations in the
of sedimentation in the same region are well illustrated by th

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[1] Ulrich and Schuchert, loc. cit., p. 637.

[2] Dawson, Bull. Geol. Soc. Am., Vol. XII, pp. 64–8.

[3] Folios U. S. Geol. Surv.; also Prosser, Jour. Geol., Vol. VIII,

[4] Keyes, Am. Geol., Vol. XXIX, pp. 384–7.

[5] King, Geological Exploration of the Fortieth Parallel, Vol. I.

of beds in the Upper Cambrian of Wisconsin. In this state the formation had an original thickness of a thousand feet or so (less than this at its original margin), though within the area where it is now exposed its thickness is usually less. It is made up chiefly of sandstone, is indeed generally known as the Potsdam sandstone; but it is much less uniform from bottom to top than this name might suggest. The following section[1] represents the general sequence of beds in the south-central part of the State:

	Feet.
6. Sandstone (Madison)	35
5. Limestone, shale, and sandstone (Mendota)	60
4. Sandstone, calcareous	155
3. Bluish shale, calcareous	80
2. Sandstone, slightly calcareous	160
1. Very coarse sandstone, non-calcareous	280

The second division of the series from the bottom suggests either that conditions were such that shell-bearing life was rather more abundant than at first, or that the waters were more highly charged with lime carbonate. The third division, the bluish shale, shows that the sediments accumulating where this section occurs were finer than those which preceded or followed. This might mean either that the water was here temporarily deeper, or that the land from which the sediments were being derived was lower, so that finer sediment only was supplied. The fourth division represents a return to the conditions favorable for the accumulation of sand, while the fifth indicates that conditions had so changed that accumulations of sand alternated with those of mud and limestone. Toward the close of the period, there was a return to conditions favorable for the deposition of sand. Even this does not represent the full measure of the variations, for within each of the several subdivisions mentioned there are minor variations. These are often brought into prominence when the rock weathers (Fig. 100). Similar variations are repeated in many places for comparable thicknesses of rock, and each change in sedimentation probably indicates a change in the geography of the period.

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[1] Geology of Wisconsin, Vol. I, p. 259.

Igneous Rocks.

At a few points igneous rocks are known to be associat stratified rocks of the Cambrian system. This is true in so Newfoundland and Massachusetts. Igneous rock is also with some of the rocks thought to be Cambrian, lying west o ern continuation of the Green mountains. Considerable of igneous rock occur west of the Gold ranges in British

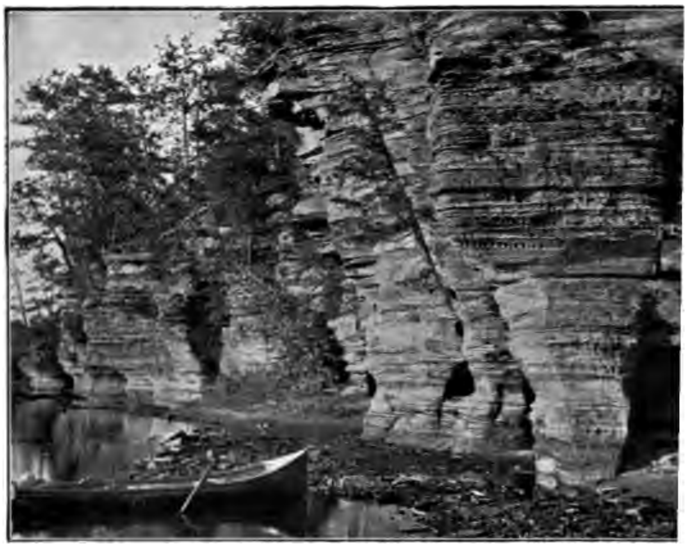

FIG. 100.—Figure showing inequalities of layers as shown by weathe sandstone, Dells of the Wisconsin. (Atwood.)

It is not always possible to tell whether igneous rocks ass the Cambrian strata were erupted in the Cambrian perio later time.

Distribution, Thickness, and Outcrops of the Cambrian

The Cambrian formations were once as wide-spread as t seas themselves, but it does not follow that they now exist areas they once covered. Where exposed, the Cambrian suffered erosion, and the border of the system, as it now a

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[1] Dawson, Bul. Geol. Soc. Am., Vol. XII, p. 85.

the areas of pre-Cambrian rock, is not its original border, and does not represent the shore-line of the Cambrian sea when its waters were most wide-spread. Fig. 101 represents the conditions which often exist. Each of the Cambrian formations, represented by *A*, *B*, and *C*, formerly extended farther to the left.

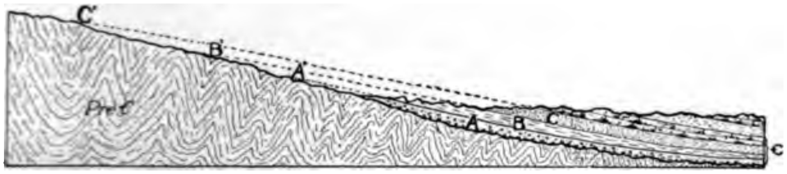

FIG. 101.—Diagram illustrating the relation of Cambrian formations, Ꞓ, to older rocks. The diagram suggests that the Cambrian formations have been eroded back from the original margins; thus *A* once extended to *A'*, *B* to *B'*, *C* to *C'*.

The areas where the Cambrian formations are exposed are not to be confounded with the areas where they actually exist. In Fig. 95 both these classes of areas within the area of North America are represented. The Cambrian formations are exposed, for example, in Wisconsin, in Missouri, and in Texas; but the strata of Texas are doubtless continuous beneath younger formations with those exposed in Missouri, and those of Missouri with those in Wisconsin, and these in turn with those of the Black Hills on the west, and with those of New York on the east. The diagrammatic section shown in Fig. 102 suggests the relations which are believed to exist. By far the larger part of the surface on which Cambrian formations were deposited was afterwards covered by younger formations. In so far as these overlying formations have not been removed, the Cambrian formations are still buried. This is doubtless true to a greater extent for the ocean bottom than for the continents.

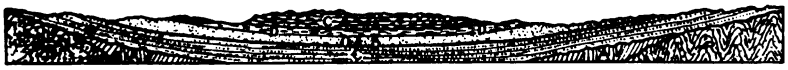

FIG. 102.—Diagram illustrating the general relations of Cambrian beds in the interior. The Cambrian, Ꞓ, is represented as appearing at the extremes of the diagram, and as dipping below younger beds between.

Position of outcrops.—The study of the maps (Figs. 90 and 95) showing the areas where the formations of the Cambrian system are now exposed reveals several points of significance. In the first place, the outcrops of the formation occur for the most part in association with

the Archean and Proterozoic systems (compare Figs. 38 an
some places, the exposed Cambrian borders the exposed pa
older systems on one side only, while in others it completely
them. Thus in the Black Hills of South Dakota, and in t
mountains of Wyoming and Montana (Fig. 94), the Cambr
tions, as now exposed, completely encircle areas of pre-Cam
In New York, Wisconsin, Texas, and British Columbia the
beds nearly encircle areas of older rocks, while in various o
the Cambrian appears in linear belts along the sides of areas
rock is of greater age. This distribution is not peculiar to the
but is characteristic of most formations as compared wit
greater age.

The areas of Cambrian rock in the Appalachian mounta
contrast with the foregoing. Here the exposed Cambrian
are not confined to the immediate borders of pre-Cambrian
occur in parallel or sub-parallel belts (Fig. 95). This is the r
the folding to which the Cambrian and later strata of this
been subject, and (2) the erosion which the folds have suffere
will help to explain the repetition of outcrops. In this
represents pre-Cambrian strata, Ꞓ represents the Cambri
S, *D*, and *C* the Ordovician, Silurian, Devonian, and Ca
systems, respectively. After strata are folded, erosion ma
down to any extent. The truncation of a fold below the
Cambrian leads to the exposure of two belts of that syst
either side of a pre-Cambrian axis, as represented in the lef
of the figure. If the truncation was at a level below the top
the bottom of the Cambrian (right-hand side of Fig. 103), t
that system are exposed in a single belt along the crest of t
parallel folds of unequal height occur, their truncation mig
to two belts of surface Cambrian in some cases, and in others
as illustrated by the figure.

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[1] For details concerning the Cambrian system of the Appalachians
lowing folios of the U. S. Geol. Surv.: Gadsden, Ala. (Hayes); Ringgo
(Hayes); Estilleville, Ky.–Va.–Tenn. (Campbell); Briceville, Tenn. (
tanooga, Tenn. (Hayes); Cleveland, Tenn. (Hayes); Kingston, Tenn. (
ville, Tenn.–N. C. (Keith); Maynardville, Tenn. (Keith); Morristown,
Pikeville, Tenn. (Hayes); Bristol, Va.–Tenn. (Campbell); Harper's Fe
W. Va. (Keith); Monterey, Va.–W. Va. (Darton); Pocahontas, Va.–W. V
Staunton and Tazewell, Va.–W. Va. (Campbell).

In some other places, Cambrian outcrops are surrounded by older formations. This is the case, for example, in some places in the provinces of Mackenzie and Athabasca in Canada.[1] In such cases the Cambrian outcrops presumably represent remnants which have escaped erosion. Theoretically, they might occupy depressions in the surface of pre-Cambrian formations, or they might constitute hills (Fig. 104).

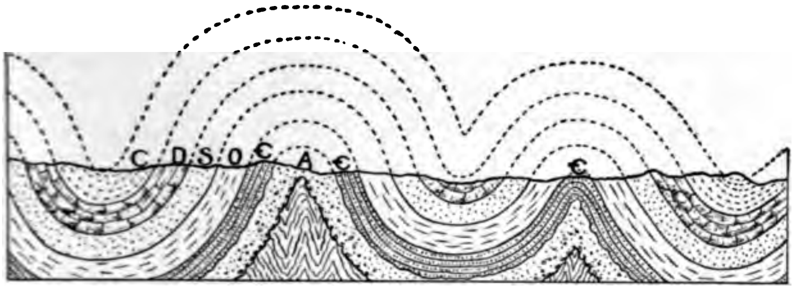

FIG. 103.—Diagram showing the positions of outcrops as determined by folds. The anticline at the right is represented as having been truncated in such a way as to expose the Cambrian, Ꞓ, in a single belt. The anticline to the left has been cut so as to expose pre-Cambrian formations, *A*, beneath, and the Cambrian, Ꞓ, outcrops in two belts, one on either side of the older formation.

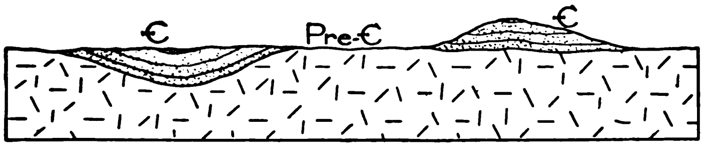

FIG. 104.—Figure to illustrate the occurrence of Cambrian in isolated areas surrounded by older formations. The diagram illustrates two ways in which such isolated areas may occur.

Again, more or less circular areas of exposed Cambrian are locally surrounded by the outcrops of younger formations, as at some points west of Hudson bay. An explanation of such areas is suggested by Fig. 105.

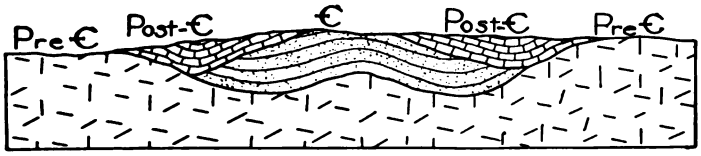

FIG. 105.—Diagram illustrating how an isolated area of Cambrian may be surrounded or bordered by younger formations.

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[1] Geological map of the Dominion of Canada, Western sheet, edition of 1901.

Width of outcrops.—Certain other principles of geologi
raphy are illustrated by the outcrops of the Cambrian sy
most extensive continuous outcrops (Fig. 95) are in Wis
yet in that State the Upper Cambrian only, with a thickness
1000 feet (see Fig. 96) is present, while in the Appalachian
where the Upper, Middle, and Lower Cambrian are all prese
aggregate thickness of several thousand feet, the system ap
surface in narrow belts only. That is, the outcrops are na
east where the system is thick, and wide in the interior whe
From Fig. 95 it is also seen that in various parts of Ne
Montana, and British Columbia, where the system is ma
thick as in Wisconsin, the outcrops of the system are much

The explanation of this apparent anomaly is to be foun
in the attitude of the strata. In Wisconsin they are nearly
while in the mountain regions, both east and west, they are
at high angles. Where the strata are vertical or nearly so, t
their outcrop on a horizontal surface is about the same as t
of the beds, as shown in Fig. 103 and the right-hand side
Where they are nearly horizontal, as in the left-hand side

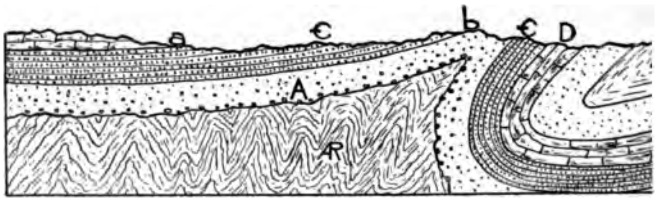

Fig. 106.—Diagram illustrating the influence of dip on the width of
Cambrian beds, Ꞓ, to the left have a much wider outcrop than the
to the right, though the thickness is the same.

the width of the outcrop is much greater. Thus in the
mountains, where the thickness of the strata is locally as
miles, their high inclination reduces their outcrop to a
while the corresponding strata in Wisconsin, less than 100
but nearly horizontal, have a much wider outcrop.

It is not to be inferred, however, that horizontal strata
determine a wide outcrop. The width of the outcrop is als
by topography, as shown in Fig. 107. Here the horizon
between *B* and *C* has about the same thickness as *C* of F

a much narrower outcrop. In general, the width of outcrop for a formation of given thickness, so far as determined by topography, depends on the angle between the bedding-planes and the surface where the formation outcrops. The width of the outcrop decreases as this angle increases.

In an area such as Wisconsin, it is not to be supposed that the edge of the Cambrian, as it laps up on older formations, represents the most advanced shore-line of the Cambrian sea. The sea doubtless extended farther up on the older land, depositing sands and other sediments on its surface; but in the long periods of erosion which have ensued, the edge of the formation as originally deposited has been destroyed (Fig. 101). Except in those cases where strata are absolutely vertical or horizontal (and few strata occupy either of these positions), the lowering of the surface by erosion must always shift the position of the outcrop of any formation, and almost always in its direction of dip.

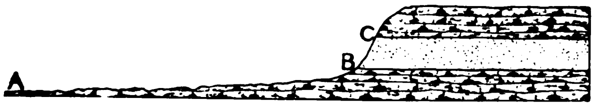

FIG. 107.—Diagram illustrating the effect of topography on the width of the outcrop.

Thickness.—Reference has already been made to the thickness of the Cambrian system in some parts of the continent, and the relative thickness in different portions of the continent is graphically represented by the sections of Fig. 96. These sections show the thickness to be great in the mountain regions of both the east and west. In the former region, the system attains a maximum known thickness of about 12,000 feet (more than two miles), and in the latter of something like 40,000 feet[1] (west of the Gold ranges in British Columbia), while over the interior it rarely exceeds 1000 feet. The greater thicknesses were probably accumulated near the shores of relatively high lands, where the supply of sediment was great.

Infirm Deductions from Thickness.

The literature of geology is by no means free from infirm deductions based on the reputed thicknesses of sediments. For example, when 40,000 feet of beds are assigned to the Cambrian section west of the

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[1] Dawson, Bull. Geol. Soc. Am., Vol. XII, pp. 62 and 64–8.

Gold range, or 50,000 feet to the Keweenawan, and when thes
show signs of deposition in comparatively shallow water, it is c
inferred that the bottom of the basin of deposition sank d
deposition to an amount corresponding approximately to th
thicknesses. Now these are depths much greater than th
parts of the oceans. Moreover, they are depths where high
tures should be experienced,[1] and where the pressure shou
the elastic limit of all known rock (estimated at about 30,
and all crevices and pores should be obliterated and the rock
pressed into complete continuity, and highly metamorphosed
face of these rather startling inferences, two attitudes have
On the one hand, the correctness of the measurements or es
these great thicknesses has been questioned, as the basal pa
thick series do not show these effects. On the other hand,
the measurements, in the main, far-reaching theories relative
deformations and internal dynamics have been built upon th
deep depression of the surface. It is therefore important
whether the fundamental assumption involved is correct,
the thickness of a series of beds deposited in a body of wate
measure of the depth of the basin receiving the deposits,
amount of its depression while receiving them.

One phase of the case may be clearly seen by consultin
in which the usual conditions for the deposition of sedime
border of a continent are represented. When the sea cover
tinental shelf, deposition takes place both on it and on the s
abysmal depths of the ocean, and very slightly on the deep
the ocean. When the sea is withdrawn from the surface of
nent, the shore stands near the upper edge of the abysmal sl
this has recently been the case is shown by river-channels t
across the upper surface of the present continental shelf, and
termini on the upper border of the abysmal slope. The main
is then on the slope, while slight deposition continued on t
bottom. As deposition on these abysmal slopes has gone o
out the whole history of the ocean basins, very extensive se
have been laid down. Because of the different attitude of

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[1] See Dana's Manual, pp. 451 and 469.

[2] Van Hise and Hoskins, 16th Ann. Rept. U. S. Geol. Surv., also this
pp. 218, 219.

the slope, the deposits have doubtless varied much in character. They were doubtless laid down fastest, and were coarsest, when the shore stood on the slope, as it has recently done, and as it probably has usually done after periods of body deformation when the seas were withdrawn more fully than usual within the oceanic basins, and when the continents were hence more protuberant and gradation more active. On the other hand, when the thin edge of the sea lapped over the border of the continent, the deposition on the abysmal slope was doubtless slower and the deposits were composed of finer material, forming shale or limestone. These details are merely to emphasize the persistent nature of the deposition on the abysmal slopes, and its varied character. The upper portion of the deposit on the abysmal slopes took place normally in rather shallow water, and from its exposed position this upper portion must always have been especially subject to the action of ocean currents and tidal waves which tended to give it the characteristics of agitated water-deposits, which we usually interpret as shallow water deposits.

The abysmal slope usually dips from 2° to 5° and hence these are about the deposition angles of the beds laid down on it. Now when

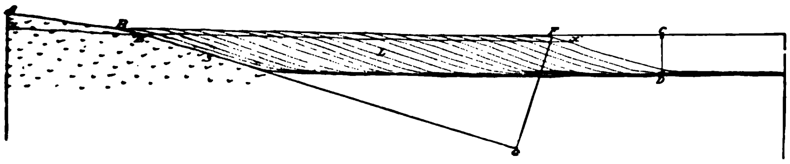

Fig. 108.—Diagram of a series of beds formed on the abysmal slope of a continent, or in similar situations, showing that the thickness as usually measured is not dependent on the depth of the basin, and that a thick series does not necessarily imply subsidence, even when the exposed portions of it show evidences of shallow-water deposition at various horizons. *A*, border of the continent, or rim of the basin; *B*, border of the depositional area; *C*, ocean-level; *D*, ocean-bottom previous to deposition; *S*, slope of abysmal basin at the beginning of deposition; *EF*, surface developed by erosion after emergence; *L*, beds deposited in sloping attitude; *EFG*, triangle by which the thickness of the series is measured; *FG*, computed thickness of beds. When compared with *CD*, the depth of the basin, a marked difference will be seen, and it will be obvious that the difference will vary with the length of *EF*.

these beds have become accessible by deformation and truncated by erosion, they are measured along the surface, which may be represented by the line *EF*, Fig. 108. There are two common modes of measurement: (1) The beds are measured individually, or by groups, at right angles to the bedding-planes, and the sum of the whole ascertained; or (2)

the average dip of the beds is taken and the distance across
cated edges, *EF*, is measured and the thickness of the whole
by trigonometry. The angle at *G* being a right angle, the angle
the side *EF* being known, the length of *FG* is readily ascerta
this is the thickness of the series, as usually measured when
ness is great. By comparing the line *GF*, representing the
of the series, with the line *CD*, the depth of the ocean, a marked
will be seen. Moreover, consideration will show that the
may vary indefinitely, and that there is no necessary relatio
the two. If the line *EF* be short, as it would be if the serie
been built far out, the thickness *FG* would be less than the de
ocean, *CD*; but if the line *EF* be long, as it would be if deposi
continued sufficiently, the thickness of the series, *FG*, woul
portionately increased, while *CD* might remain constant.
words, *the thickness of the series may vary from any fraction o*
of the basin to any multiple of it, within certain limits impos
width of the basin.

Similar considerations reveal a discrepancy between th
measurement and the thickness of the beds deposited subaëri
example, the thickness of the beds of a typical volcanic c
than the height of the cone which they form, as will be seen fro
Lava-flows poured forth on heights, and congealing as they
upon the slopes below, may give rise to series of great aggre
ness, without implying any contemporaneous sinking or ot
change. Clastic beds formed by slope-wash may become i
between these lava-flows without implying subsidence. In
the *horizon of wash is shifted* to higher and higher positions i
(not necessarily to higher altitudes), but the *series of beds is*
In the case of the Keweenawan system, a congelation or
slope of 5°, extended horizontally a little over one hundre
about half across the Keweenawan basin, as it may have b
compression, would give the estimated thickness (see p.
explain the present attitude, it is necessary to suppose that
was compressed laterally, so that the beds were upturned and
sheared upon one another (Fig. 110). A greater upturnin
course be supposed, if the alternative view is taken that
were originally strictly horizontal.

It is not here affirmed that this is the explanation of th parent thickness of the Keweenawan series, certainly not that it is the whole explanation, though it seems to throw important light on it. The point here made is merely that great apparent thickness may and does arise in this way, and that inferences and doctrines that overlook this fact have an insecure basis.

In the case of such sedimentary beds as are formed on mountain slopes, the sides of intermontane valleys, or in other situations where there is an appreciable deposition angle, the thickness of the beds varies indefinitely in comparison with the vertical range of the deposit.

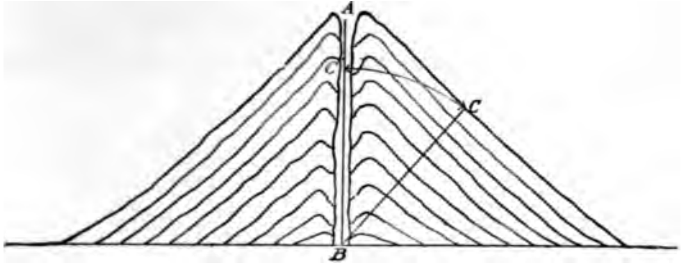

Fig. 109.

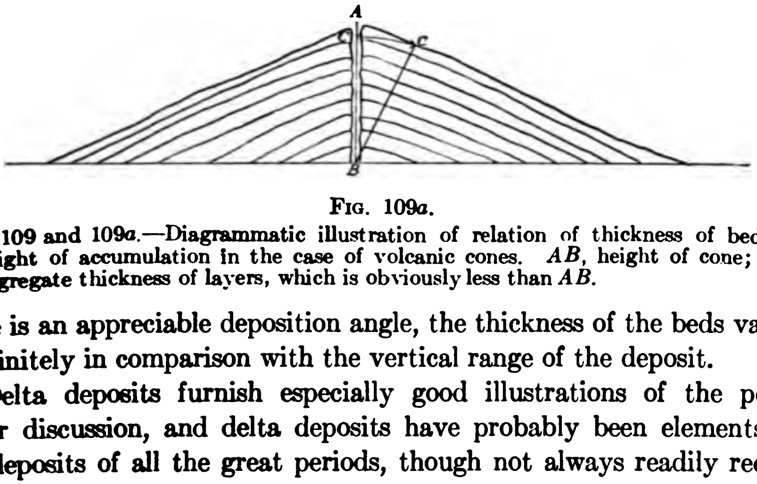

Fig. 109a.

Figs. 109 and 109a.—Diagrammatic illustration of relation of thickness of beds to height of accumulation in the case of volcanic cones. *AB*, height of cone; *CB*, aggregate thickness of layers, which is obviously less than *AB*.

Delta deposits furnish especially good illustrations of the point under discussion, and delta deposits have probably been elements in the deposits of all the great periods, though not always readily recognizable in their buried condition. If the Amazon were to build out a delta 200 miles, the ocean bottom remaining absolutely immovable at an average depth of four miles below the surface, and the deposition angle were to be on the average 2°, the computed thickness of the series, according to current methods of measurement, would be about seven miles. If the delta were built out 1000 miles, the computed depth would be thirty-five miles. In a lake 100 miles wide and 1000 feet deep, in which the deposition angle was 3° on the average, and in which the filling grew outward from each shore fifty miles, meeting in the center, the thickness of the series on each side, measured by the a dard method, would be 13,800 feet, no change at all in the the surface of the lake being assumed. If the Nile should eastern end of the Mediterranean, the Danube the Black se Mississippi the Gulf of Mexico, with no essential change in t of the basins or the surfaces of the water-bodies, series of b digious thicknesses, as thicknesses are commonly estimated, the result. The usual changes in the sea-bottoms, chang upward and downward phase, might take place during the filling, without seriously affecting the result.

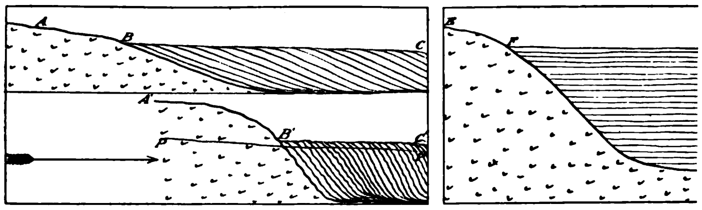

FIG. 110.—Diagrammatic section illustrating the assigned change of a series of beds, like the Keweenawan, from an original depositiona to a more highly inclined attitude, a comparatively simple change. were laid down horizontally in a sinking basin, as illustrated at the obvious that a greater and a more complicated movement would be bring the beds into the attitude represented in the lower figure at th represents the present attitude of the Keweenawan beds.

Dwelling on these aspects of the case, we almost reac clusion that the thickness of a series of beds, *as we usual thicknesses where they are great*, is independent of the depth of This, however, is pushing the case too far, for the consider have been urged apply only to deposition of the kinds spe *deposition on appreciable slopes*. When deposition takes strict superposition in horizontal attitudes, the usual infe correspondence between the depth of the basin, or the sin bottom, and the thickness of the series, holds good. More the beds above and below are accessible, or penetrable such as wells, over large areas, the vertical depth of depositi conclusively ascertained. This is usually the case with t of the broad shallow epicontinental seas. In them, obli tion is usually a minor phenomenon. But the deposits of t epicontinental seas, laid down on plane surfaces, should not with the deposits built out on the border slopes of the deep b

Applying these considerations to the varying thicknesses of the Cambrian beds, it is to be observed that any deep portion of the seas, not simply the ocean border, which was filled from the side by a gradual building out on the slopes, was liable to develop a thickness of beds disproportional to the depth of the water. At the same time, the superposition of great sheets of sediments covering broad epicontinental areas, as those of the interior in late Cambrian time, was probably rendered possible only by a change in the relation between the sea-bottom and the sea-surface. This change probably consisted in part in a raising of the sea-surface by sea-filling, and in part in the sinking of the surface on which the sediments were deposited.

The apportionment of the relative influence of these several factors in the development of the observed thicknesses of rock is a difficult matter, requiring a careful study of all available sources of evidence to be found in the character of the deposits, in their relations to overlying and underlying formations, and in the topography of the Cambrian sea-bottom, so far as it can be reconstructed. Unless the interpretation can be made with great assurance of correctness, inferences as to crustal movements based simply on the thicknesses of deposits may well be entertained with reserve, and doctrines based on extreme subsidence inferred from these thicknesses may well be regarded as lacking a firm basis.

Selected Sections.

The following sections of the Cambrian, at widely separated points, give some idea of the range of the system both as to thickness and kinds of rock, and therefore of the variations in the conditions and in the rate of sedimentation.

Section in Southeastern Newfoundland.[1]

	Thickness in Feet.	Characteristics.
Middle and Upper Cambrian.	476	Brown and black micaceous shales, with gray micaceous sandstones; Bell island, Concepcion bay.
	1426	Red and green sandstones and slates, with calcareous beds at the base.
	720	Kelly's Island sandstones and shales, containing a few fucoids.
	150	Black slate or shale; Middle Cambrian fossils.
	5	Dark-gray limestone.
	1045	Red, green, and black slates or shales; Middle Cambrian fossils.

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[1] Walcott (section after Murray), Bull. 81, U. S. Geol. Surv., pp. 257–8.

SECTION IN SOUTHEASTERN NEWFOUNDLAND.—*Contin*

	Thickness in Feet.	Characteristics.
Lower Cambrian.	100	Hard thick beds of gray, and sometimes r Lower Cambrian fossils.
	250	Red, green, and blackish argillaceous slates
	50	Conglomerate of Manuel's brook, not recog
	150	Red and green argillaceous shales or slates.
	20	Red and flesh-colored limestone; obscure fo
	30	Red slate.
	10	Impure limestone.
	40	Red slate.
	750	Red, green, and gray sandstones, with oc conglomerate; upper beds flaggy.
	137	Green and reddish-brown or purple slates.
	3	Impure flesh-colored limestone.
	10	Green slate.
	600	Hard, dark, green-gray thin-bedded sands divisions.
	Unconformity. Proterozoic and Archean.	

Strata dip at low angles.

SECTION IN WESTERN VERMONT.[1]

	Names of Formations.	Thickness in Feet.	Characteristics.
Upper and Middle Cambrian.			Cut off by a fault above.
		3500 to 4500	Arenaceous shales.
		1700	Massive gray limestone, with i of hard argillaceous shale.
		50	Light-gray quartzite.
		3500	Argillaceous shales; occasion hard gray limestone; numer a linguloid shell.
Lower Cambrian.	Georgian shales.	200	Argillaceous, micaceous, and a numerous Lower Cambrian f
		190	Gray arenaceous limestone in layers, passing into more light-gray arenaceous lime ous.
	Red Sandrock series........	100	Reddish-pink dolomitic limest
		475	Massive gray dolomitic limesto
		200	Steel-gray dolomitic limeston mottled limestone; some red
		35	Massive bluish gray dolomiti threads and bunches of yell limestone that weathers in r
	Base unknown.		

Strata dip at high angles.

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[1] Walcott, Bull. 81, U. S. Geol. Surv., pp. 277–280.

SECTION IN MASSACHUSETTS.[1]

	Names of Formations.	Thickness in Feet.	Characteristics.
Middle Cambrian.	Braintree section..	1000 −	Conglomerate of quartzite pebbles and sandstone.
		500 to 1000	Greenish-gray, fine-grained, siliceous slates; Middle Cambrain fossils.
	Discontinuity.		
Lower Cambrian.	North Attleboro (belongs below Braintree section).	2000 ±	Thin-bedded shales which occasionally pass into fine-grained greenish and reddish slates; a few beds of conglomerate varying from 200 to 300 feet in thickness; some beds contain Lower Cambrian fossils; little metamorphosed.
	Unconformity. Archean.		

Strata dip at high angles.

SECTION IN NORTHERN NEW JERSEY.[2]

	Names of Formations.	Thickness in Feet.	Characteristics.
	Trenton formation. Unconformity.		
Upper and Middle Cambrian.	Kittatinny limestone. Upper part = Lower Ordovician. (Lower part = Lower Cambrian.)	2700 to 3000	Blue or gray, sometimes nearly black limestone, variable in texture, composition, and color; arenaceous at base.
Lower Cambrian.	Hardiston quartzite...	0 to 185	Sandstone, quartzite, locally arkose; intercalated beds of shale and dolomitic limestone; Lower Cambrian fossils.
	Unconformity. Pre-Cambrian.		

Strata gently folded.

The published sections of the Cambrian of Texas are not altogether in accord.[3] The Middle and Upper Cambrian series are represented by sandstone and lime-

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[1] *Ibid.*, pp. 268–73; and 10th Ann. Rept. U. S. Geol. Surv., p. 567.

[2] Kümmel and Weller, Bull. Geol. Soc. Am., Vol. XII, pp. 147–154.

[3] Walcott, Bull. Geol. Soc. Am., Vol. X, p. 218; 10th Ann. Rept. U. S. Geol. Surv., p. 552; Bull. 81, U. S. Geol. Surv.; and Am. Jour. Sci., Vol. 28 (1884), pp. 431–33; and Comstock, First Ann. Rept., Geol. Surv. of Texas, 1889, pp. 285–292.

stone. The Lower Cambrian also is thought by Comstock[1] to be ı is possible that the Lower Cambrian is present at some points and no The Cambrian is unconformable on its base, and according to Comst is also unconformity between the three main subdivisions of the Caml thickness varies from point to point, the published sections giving (feet or more. Strata nearly horizontal.

In west central Colorado[2] (Tenmile region) 160 to 200 feet of whit more or less argillaceous above, represents the Cambrian system. ' tion carries Upper Cambrian fossils, and rests on the Archean unc Strata gently folded.

In north-central Utah[3] (Tintic region) the Cambrian is represen Tintic quartzite, which has a thickness of some 7000 feet. Since th is not known to carry fossils, and since it is conformably overlain iferous formations, it may not all be Cambrian. Strata much fold

In the Wasatch Mountains[4] the Cambrian rests conformably on t zoic. The Lower Cambrian is represented by slate 75 to 600 feet t slate is overlain by the thick Ute limestone, 1000 to 2000 feet thick. shaly part only of this formation contains a Middle Cambrian faun Upper Cambrian fauna is not known. The larger part of the Ute I Ordovician, and its top may be Silurian. Strata much folded and fau

In the Rocky mountains of Canada the following Cambrian secti

Names of series.	Thickness in feet.	Characteristics.
Castle Mountain series.	8,000	Consists of limestone, dolomites, shales, slates, The lower part carries Lower Cambrian fos uppermost part fossils which appear to be
Bow River series.	10,000	Chiefly argillites with some sandstone, quartzi glomerate. Lower Cambrian fossils occu below the top.

Summary of physical events and interpretations. — The lation of a thick series of beds in certain regions and the of a relatively thin sheet over a large part of the American are matters of positive determination. The immediate a which this was accomplished is found in the wear of the lan deposit of the débris in the adjacent seas. The remoter agencie nished the conditions under which the erosion and the deposition took place are less certain, and have been assigned to different sources by different investigators. The preponderant tendency has been to give a leading place to crustal movement. On the other hand, in the previous discussion a preference has been indicated for assigning the leading place to gradation, and for attributing such deformations as obviously took place to superficial causes that were largely inherited from the Proterozoic or post-Proterozoic diastrophism. On this view, the period was one of general quiescence and almost free from profound deformation. This interpretation makes the Cambrian a period of progressive base-leveling, modified in some degree by superficial deformations. The gradational interpretation has the merit of accommodating automatically, as it were, the erosion that furnished the material, to the planation that provided the nearly level expanse on which the broad sheet of the later Cambrian was spread.

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[1] See foot-note, p. 221.

[2] Emmons, Ten Mile (Colo.) folio, U. S. Geol. Surv.

[3] Emmons, Tower, and Smith, Tintic (Utah) special folio, U. S. Geol.

[4] King, Expl. of the 40th Parallel, Vol. I, p. 156; Walcott, Bull. 81, Surv., pp. 157–60. and p. 328.

[5] McConnell, Ann. Rept. Geol. Surv. of Canada, Vol. II (New Series)

Changes in the Cambrian sediments since their deposition.—Since their deposition, the sediments of the Cambrian system have undergone more or less change. In most regions the gravels, sands, and muds have been compacted and cemented into conglomerates and sandstones and shales respectively. In some places the cementation of the sandstone has been carried so far as to convert it into quartzite, though this is not the rule. Over great areas in the interior (Missouri, Wisconsin. Texas, etc.) the strata still remain in horizontal or nearly horizontal position (Figs. 102 and 107), while in other regions they have been tilted and even folded. Where close folding has taken place, the

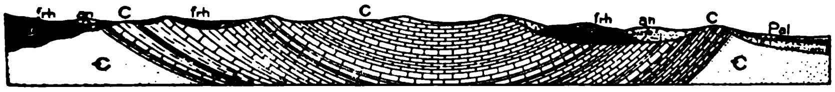

FIG. 111.—A section showing the relations of the Cambrian at one point (near Tintic) in Utah. Ꞓ, Cambrian; *C*, Carboniferous; *frh*, rhyolite; *an*, andesite; *Pal*, Pleistocene formations. Length of the section, about 6 miles. (Emmons, Tintic (Utah) folio, U. S. Geol. Surv.)

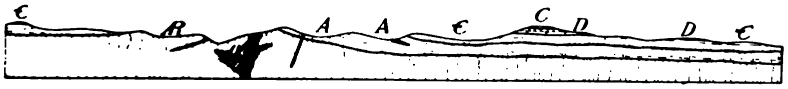

FIG. 112.—Section showing relations of the Cambrian at a point in Montana. *Æ*, Archean; *A*, Proterozoic; Ꞓ, Cambrian; *C*, Carboniferous; *D*, Devonian. Length of section, about 20 miles. (Weed, Little Belt (Mont.) folio, U. S. Geol. Surv.)

dynamic action involved has had a metamorphosing effect on Thus in the mountains of the eastern part of the United

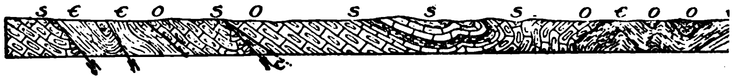

FIG. 113.—Section showing the relation of the Cambrian in the Appala tains. The strata are both folded and faulted. €. Cambrian; *O*, *S*, Silurian. Length of section, 13 miles. (Hayes, Cleveland, Tenn. Geol. Surv. Ordovician and Silurian not separated in original.)

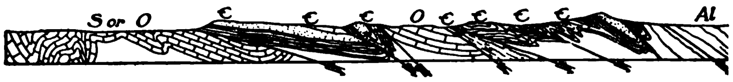

FIG. 114.—Section showing the relations of the Cambrian at another Appalachian region where the faulting has been extreme. *Al*, Pro Cambrian; *O*, Ordovician; *S*, Silurian. Length of section, abou (Keith, Harper's Ferry, Va.-Md.-W. Va. folio, U. S. Geol. Surv. Or Silurian combined in original.)

original sandstones have been converted into quartz schists, into slates and schists, and the limestones into marble where th

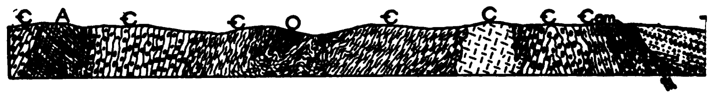

FIG. 115.—Section showing the relations of the Cambrian at a point in where the rocks are much metamorphosed. *A*, Proterozoic; €, C Ordovician; *C*, Carboniferous; *T*, Triassic; *am*, amphibolite. Le tion, about 11½ miles. (Emerson, Holyoke, Mass. folio, U. S. Geol. Su

movements were profound, and less altered where the fc simple. Fig. 102 shows the general position of the Cambı

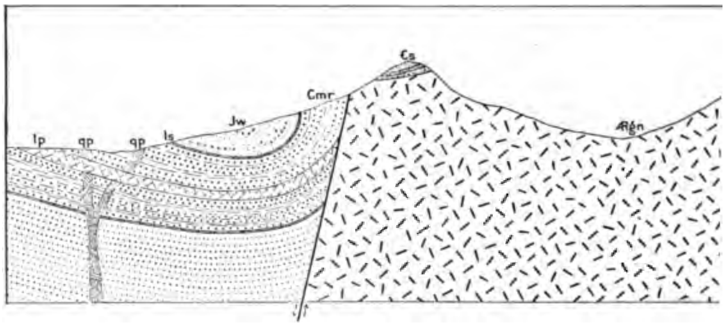

FIG. 115*a*.—Section showing the relations of Cambrian and other fon point in Colorado a little north of Leadville. *Ægn*, Archean; € (Sawatch quartzite); *Cmr*, Carboniferous (Maroon formation); (Wyoming formation); *lp* and *qp*, igneous rocks. (Emmons, U. S.

(€) over much of the interior. Fig. 111 shows their po relations in the vicinity of Tintic, Utah; Fig. 112, at a point ir

Figs. 113 and 114, at two points in the Appalachian mountains; and Fig. 115, near Holyoke, Mass. These several sections give a fairly adequate idea of the present position and relations of the system. In Figs. 102, 107, and 112 the structure of the Cambrian is relatively simple and the rocks are not metamorphosed. In Fig. 103 the beds are gently folded and erosion has discovered the Cambrian beds at the tops of the anticlines. The rocks are not metamorphic. In Fig. 113 the beds are more crumpled at the right, and faulted as well as folded at the left, and the rocks are somewhat metamorphic. In Fig. 114 close folding and faulting are represented, and the metamorphism of the rocks has proceeded farther, though not to extremes. In Fig. 115 the crumpling due to profound dynamic action is more pronounced, and here the rocks are highly metamorphic.

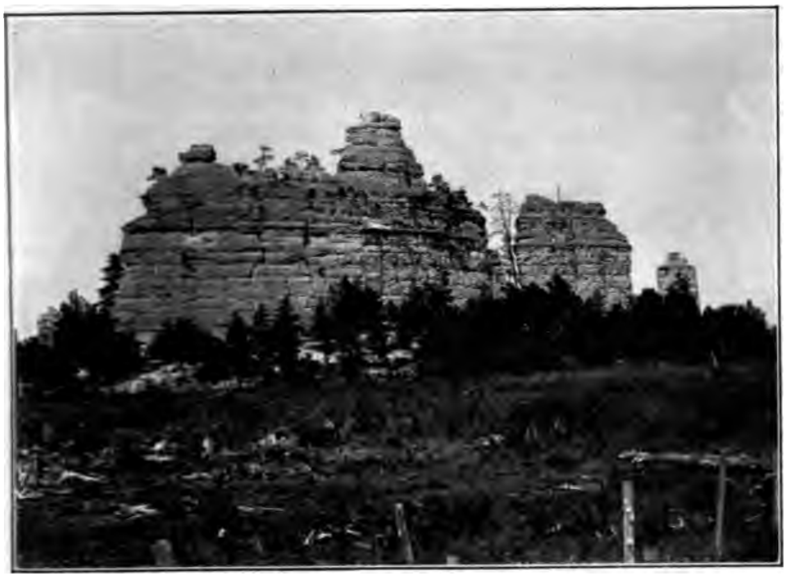

Fig 116.—Figure showing an isolated remnant (a dying hill) of Potsdam sandstone in central Wisconsin. The remnant has been isolated by erosion.

Close of the Cambrian.—No physical changes of great importance seem to have marked the close of the Cambrian period in America. Nowhere in our continent, so far as now known, were mountains made at this time, and nowhere were great areas of sea-bottom converted into land.

FOREIGN CAMBRIAN.

Europe.[1]—The only continent besides North America
been sufficiently studied to allow of definite portrayal of the
formations, is Europe. In the area occupied by this conti
is evidence that there was, as in North America, a somew
spread deformation in pre-Cambrian time, which converted
into land. Further, there is evidence that these lands, lik
America, were subjected to protracted erosion before the de
the oldest known Paleozoic formations. As a result, the
system, where its base is seen, generally rests unconformabl
strata, but in places it is so highly metamorphic as not to
distinguished from them. Occasionally, too, there may be
tion into the Proterozoic formations.

The Cambrian formations of Europe, like those of An
mainly clastic. They include conglomerates, sandstones, gr
shales and their metamorphic equivalents, quartzites, slat
etc. In some places, thick bodies of limestone, partly or wh
morphosed, are associated with the clastic beds. A conside
portion of the material involved in the clastic formations
and the strata are often ripple-marked, and affected by cro
and by sun-cracks. All these features point to the conclus
large part of the Cambrian sediments were laid down in shal
In some regions the formations are notably red, a fact whic
thought to indicate that they were formed on land or in lake
seas.[2]

The European Cambrian is notable for its extreme va
thickness. In Wales (Cambria), the country from which t
received its name, it has a thickness of 12,000 feet or m
great thickness is equalled or exceeded in Brittany, where
8000 meters in thickness are referred to the system. In wester
the thickness is 3000 feet, and in northern Scotland 2000 fee

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[1] The best summary of the Cambrian of Europe, in English, is foun
Text-book of Geology, 4th ed., Vol. II. This text gives references to t
Other recent summaries are given in DeLapparent's, Traité de Géolog
Elemente der Geologie, and Kayser's Formationskunde.

[2] Ramsey, Quart. Jour. of the Geol. Soc., Vol. XXVII, 1871, p. 25

[3] DeLapparent (Traité de Géologie, 4th ed., 119) assigns the Camb
region a thickness of 8000 to 10,000 meters.

Scandinavia, where Lower, Middle, and Upper Cambrian all are present, he aggregate thickness is sometimes no more than 400 feet. In western Russia also it is thin. These differences probably mean that ediments were being deposited in some places many times as rapidly as in others.

The commonly accepted subdivisions of the British Cambrian are 1) the Harleck and Llanberis group (Olenellus zone), (2) the Menevian group (Paradoxides zone), and (3) the Lingula flags (Olenus zone). The Tremadoc slates are sometimes classed as Upper Cambrian.

The subdivisions of the Cambrian are notably unlike in different parts of the continent. The faunal unlikenesses are such as to seem o divide the continent into two natural provinces, a northern and a outhern. To the northern division belong the areas of Cambrian rock ound in Russia, Scandinavia, and north Scotland; to the southern, hose found in Bohemia,[1] France, Spain, Portugal, Sardinia. It is commonly believed that some sort of barrier must have existed between these provinces which prevented marine life from passing freely between them. It has also been suggested that the differences in aunas between the two regions may be due, at least in part, to climate;[2] but this suggestion finds little support so far as present knowledge goes n other parts of the world. The fossils of the northern provinces of Europe have much resemblance to those of the Atlantic border of America, suggesting that geographic and climatic conditions were such as to allow of the free migration of marine life from northern Europe o eastern America, and *vice versa.*

In Europe the Middle Cambrian is more wide-spread than the Lower or Upper,[3] showing that changes in the relation of sea and land were in progress during the Cambrian period, shifting the areas of erosion and edimentation. It is a matter of interest to note that the Cambrian history of western Europe seems to have some correspondence with hat of eastern North America, while that of central and eastern Europe has more likeness to that of the interior of our continent.

The total area where the Cambrian rocks are exposed in Europe is small, and the outcrops sustain the same general relations to older ormations as in North America. The actual extent of the system is

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[1] Made famous by the classic studies of Barrande; Système Silurien de la Bohème.

[2] Kayser and Lake, Comparative Geology.

[3] Frech, Neues Jahrbuch für Mineralogie. 1899, Bd. II, pp. 164–176.

much greater than the area where it is exposed, since it is
many regions by younger formations. The Cambrian, howe
believed to underlie the younger strata of eastern Russia, an
of the continent is believed to have been mostly out of wa
the Cambrian period.

The Cambrian strata of Europe, especially of western E
often much folded. In some regions also (Britain and Britta
rocks occur at or near the base of the system. In central a
Europe, on the other hand, the formations are essentially
Beds of clay which are still plastic, and beds of sand whi
uncemented, are here found within the limits of the system.

No geographic change of great importance seems to ha
the close of the Cambrian. In this respect, as in others, th
history of Europe and North America are in general corresp

Other countries.—By means of their fossils Cambrian
known to occur in the northeastern parts of China,[1] in the
of India[2] (Lower and Middle Cambrian), in the southeaste
Australia[3] and in Tasmania (Lower, Middle, and Upper),
northwestern part (Salta) of Argentina[4] (Upper Cambrian)
of these regions the formations have not been studied in mu

Glacial formations.—In the vicinity of Varanger fjord, i
Norway, Lat. 70° 8′ N., there is a bed of bowlder-bearing
ing on a smoothed and striated pavement of the distinc
type, and embraced within an irregular clastic formation,
the Gaisa beds.[5] These beds rest upon the eroded surface c
line terrane. No fossils have been found in them and t
not positively determined. Reusch regards them as eq
the Sparagmite formation in central and southern Nor
underlies beds containing the *Olenellus* fauna, and which
either the very earliest Cambrian or earlier. The Gaisa
some resemblance to the Torridon (Proterozoic) of the B
and may be of the same age. They are of the red sand

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[1] Von Richthofen, China, Vol. III.

[2] Redlich, Palæontologica Indica, new ser. Vol. I, and Records G
India, Vols. XXII, XXIV, and XXVII.

[3] Etheridge, Proc. Roy. Soc. Tasmania, 1882–1883; Trans. Roy. S
Vol. XIII; Tate, *Ibid.*, Vol. II, XLVIII, and XV; and Johnston, Surv.

[4] Kayser, Zeit. der deutsch. Geol. Gesell., Vol. XLIX.

[5] Reusch, Norges geologiske Undersöegelse: Det nordlige Norges
Also Strahan, Quar. Jour. Geol. Soc., Vol. 53, 1897, pp. 137–146.

of which Strahan significantly remarks: "They all belong, in part, to the type prevailing in those formations which have been the first to be deposited at the close of a great continental epoch."

Recent exploration in China[1] has shown the existence, on the Yang-tse river, in latitude 30°, of a thick formation (170 feet) of bowlder-bearing rock of the typical glacial kind containing many striated bowlders of diverse sorts of rock (Fig. 116*a*). The striæ appear to be of the distinctive glacial type and the matrix in which the striated stones are imbedded is such as bear out the evidence of the stones themselves. The formation lies at the very base of the Paleozoic terrane of the region, and beneath the series that carries the Cambrian trilobites. It is therefore to be referred either to very early Cambrian, or to pre-Cambrian time. At present, the most probable interpretation is that these formations of Norway and China belong either to the transition period that accompanied and followed the deformation that closed the Proterozoic, or to the opening stages of the Paleozoic previous to the undoubted Cambrian, with some preference for the latter. Whatever their precise age, their profound significance is obvious.

From Australia[2] and South Africa[3] Cambrian or pre-Cambrian glacial beds have been reported recently.

In the rocks of undoubted Cambrian age there is little valid evidence pointing to diversity of climate. The testimony of the fossils, wherever gathered, implies nearly uniform climatic conditions not only over our own continent, but throughout all the earth where records of the Cambrian period are found.

DURATION OF THE CAMBRIAN PERIOD.

There is no way in which a reliable estimate may be made of the duration of the Cambrian period. It is safe to say that the destruction and the removal to the sea of such large volumes of rock as are represented by the sediments of the Cambrian required a very long period of time; but since there is no standard rate at which any sort of sedi-

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[1] Willis, Blackwelder, and Sargent. The above note is based on an unpublished oral statement of the results obtained during an extended exploration under the auspices of the Carnegie Institution. See also Year Book No. 3, Carnegie Inst., p. 382.

[2] Howchin and David, Rept. Austral. Assn. for the Adv. of Science, Vol. IX, 1902.

[3] Schwarz, Jour. of Geol., Vol. XIV, p. 683, 1906.

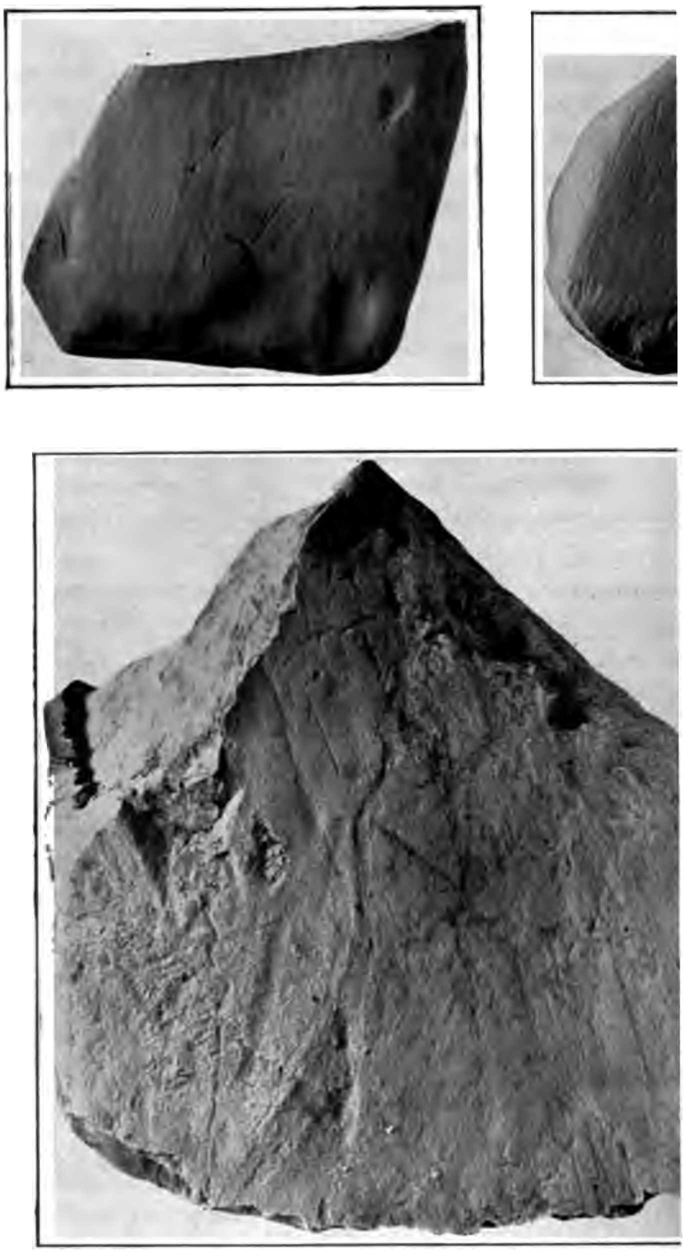

Fig. 116a.—Glaciated stones from the glacial beds at the base of China. (Willis, Carnegie Institution.)

nt is known to accumulate, this long period cannot be reduced to ars. It is quite certain that the rates vary greatly. Besides many vious illustrations of the minor sort, there is this very general and portant one: When the land is relatively broad and high, and while e deposition belt around its borders is narrow, as is apt to be the se after a period of continental protrusion, the amount of material oded in a given time is likely to be large, while its concentration on e limited deposition area necessarily gives great proportional thickss and rapidity of rate to the accumulation. On the other hand, hen the continent is approaching base-level, and the land is low and nited by the encroachment of the epicontinental seas, and while these as are wide and shallow, and subject to agitation over broad tracts, e amount of material eroded in a given time is relatively small, while e area over which it is spread is exceptionally large, and hence it adds ut slightly and slowly to the thickness of the deposits. In Washington ounty, N. Y., there is a bed of Cambrian limestone 1400 feet thick neath 10,000 feet or more of fragmental rock. It has been estimated at limestone sometimes forms at some such rate as one foot per ntury.[1] At this rate this limestone alone would have required 40,000 years. If the overlying fragmental rocks required an equal ngth of time for their accumulation, the total length of the period ould be 280,000 years. In some parts of the West there are 6000 feet limestone besides thick bodies of fragmental rock. At the same rate accumulation, the 6000 feet of limestone would call for a period of 0,000 years, and if time be allowed for the other formations of the me region, the period would be greatly lengthened. It should be remem- red, however, that while one foot per century may be a rate at which nestone sometimes accumulates, it does not follow that it is the rate which the Cambrian limestones were formed. The data on which is estimated rate is based are believed to give too high, rather than too w a rate, and a less rapid accumulation would mean a correspondingly nger period of time.

Many estimates of geological time, based on various data, have en attempted.[2] These estimates, so far as applied to the Cambrian, nerally assign to that period a duration of 1,000,000 to 3,000,000 years. should be distinctly borne in mind, however, that the chief value

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[1] LeConte, Am. Jour. Sci., Vol. X, 1875, p. 34.

[2] For a general discussion of this matter, see Williams' Geological Biology.

of these figures is to give emphasis to the fact that the perio
of great duration.

THE LIFE OF THE CAMBRIAN.

Perhaps no single event in the history of the earth posses
interest than the first appearance of life. We have alrea
that the real advent of life on the globe has not been revea
record, as thus far known, and there is almost no hope that i
be. There is good evidence that life existed in the several gr
of the Proterozoic, and in some at least of those of the
Under the accretion hypothesis, it is not improbable tha
beginning of life on the earth greatly antedated even the ol
accessible Archean formations. If so, it is quite beyond
the great problem of the earliest forms of life will ever be
direct fossil evidence. Even in the Archeozoic and Prot
evidences of life, while sufficient to create a firm convictio
earth was then tenanted by living things, are so indirect
that they give very little idea of the nature of the life.
information as the imperfect fossils give, carries in itself evi
it does not tell the whole story, or even the main part of
life imperfectly represented could not have lived without o
of life which are not represented.

The first fair record.—In the Cambrian, for the first time
fair preservation, in fossil form, of the life of the period.
the record is very far from complete, but it is an immeasurab
on the records of previous periods. Something of the in
importance that would have attached to the earliest forms
they been preserved, is therefore transferred to this first legi
Preliminary to a review of this record, the chief ways in whi
on questions of fundamental interest may receive a mon
sideration.

What stage of evolution is represented?—Foremost a
questions that arise is the stage of development that had b
attained by life, when thus first fairly preserved. Was th
primitive, implying that it was not far removed from th
forms of life, or did it bear signs of great previous evolution

The stage of evolution attained may be estimated (1) by of development of the various organic structures and functions, and (2) by the amount of divergence of the animal types.

(1) For comparison it may be assumed that the primitive forms were at least as simple as the simplest existing forms. Among these there are organisms which are scarcely more than aggregates of living protoplasm, almost devoid of any permanent and recognizable organs. There are also multitudes of plants and animals that consist of a single cell only. If these be taken as representing the nearest existing approach to primitive forms, a comparison between them and the complicated structures shown by many of the Cambrian fossils, presently to be described and illustrated, will give some impression of the degree of advance in organization that had been attained.

But we are not left entirely to this mere presumption that the earliest forms were much simpler than the Cambrian, for the stages of development of the young of certain of the Cambrian animals reveals something of their ancestral history. It is a well-established law of embryology that animals in their pre-natal and youthful development pass through a succession of stages in which their structure resembles that which their ancestors had in their maturity; in other words, that the individual history of each animal is an epitome of the collective history of its ancestors. Now the trilobites (Fig. 118), the leading form of Cambrian life, are known to have passed through a series of quite remarkable changes after they became well enough developed to be fossilized, and doubtless they passed through other stages previously. There is, therefore, specific ground for believing that they had a long line of ancestors.

(2) The studies of recent decades have convinced investigators that the later forms of life have been derived from earlier ones by some process of evolution. The exact nature of the process is yet under investigation, but the fact of derivation is not now regarded as an open question. As the various forms developed and diverged, many of the intermediate gradations were dropped out, because of inferior fitness, or from some other cause, and thus the diverging forms became separated from one another. As these divergent branches themselves developed later, they in turn diverged, and the intermediate forms disappeared, and thus a succession of branches was developed. By such continued divergence and loss of intermediate forms, a more and more complicated system of branching was developed. Not only

were the intermediate or connecting forms dropped out, bu the branches themselves disappeared, and the remaining on more and more widely distinct from one another. The pr not unlike the evolution of a tree-top, in which the dying o of the interior branches leaves a few great limbs which bear numerous and more recent branches, while these in turn bear most and outermost twigs which represent the living phas way, or in some such way, it is thought that the existing of organisms into kingdoms, branches, classes, orders, famili species, and varieties came to be established.

If it be assumed that the whole system of living things derived from a common primitive form or a few primitiv comparison of the primitive state with the degree to which d and the loss of the intermediate forms, had gone in the Camb will give some impression of the amount of evolution alrea plished. If to this be added a comparison between the Ca and the present life, an estimate of the relative amount of before and since the Cambrian period may be made. T especially instructive, as it will give some impression of t importance of the pre-Cambrian and the post-Cambrian p the earth's history, measured by life development.

To be sure, it cannot be assumed safely that the rate of in early and in late times was precisely the same, or that the of one branch proceeded at the same rate as that of other for there certainly were marked differences; but notwithsta a general and not altogether incorrect impression of the re portance of the unknown pre-Cambrian evolution, and of t post-Cambrian evolution may be derived, and this, notwit all elements of uncertainty, is of no small value.

The scantiness of plant fossils.—On the most general of the record there appears at once an obvious inconsisten the animal kingdom is fairly well represented, while plan are barely identifiable; indeed, their presence would perhaps b if there were not imperative reasons for believing that they we in abundance. As all animals are dependent directly or ind plants for food, it must be supposed that plants were presen cient numbers not only to support the animals, but to furnish since a portion inevitably escaped consumption by the anim surplus might not be worth noting if there were not specific reasons for regarding it as large. Not a few of the Cambrian animals were fixed to the bottom of the sea, and hence there must have been organic matter enough floating in the water to bring them their daily food, and this implies *a very general enrichment* of the oceanic waters with plants. Probably these were largely minute one-celled plants of the algæ type, and hence they easily escaped fossilization. The inadaptability of the lower plants to fossilization is doubtless the chief explanation of the poor representation of the plants among the Cambrian fossils.

Reasons of a physical nature have previously been given (p. 217) for thinking that the surface of the land was clothed with some kind of vegetation, and this is an additional reason for assuming a very general, if not nearly universal, distribution of plants over the surface of the globe. But there are no identifiable traces of land-plants, and but very obscure impressions of sea-plants. There are some ill-defined stem-like or frond-like impressions, commonly styled "fucoidal," that may be, in part at least, the casts of sea-weeds. A peculiar form consisting of clusters of radiating rays (*Oldhamia*, Fig. 117) is found in abundance in Cambrian rocks in Ireland, and has been referred to algæ, but the identification is not beyond question. These and a few other doubtful forms make up the whole record as thus far revealed. The lesson taught is the extreme imperfection of the fossil record.

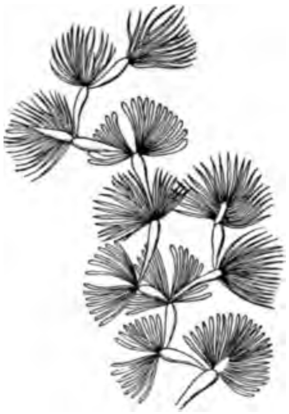

FIG. 117.—*Oldhamia antiqua* Forbes, a problematical organism most commonly referred to marine algæ, but it may possibly belong to the zoophytes.

THE ANIMAL FOSSILS.

Turning to the record of animal life, it appears by contrast that every great division of the animal kingdom, except the vertebrate, had its representatives in Cambrian times. The *Arthropoda* were represented by crustaceans; the *Mollusca*, by cephalopods, gastropods, pteropods, and pelecypods; the *Molluscoidea*, by brachiopods and bryozoans; the *Vermes*, by annelids; the *Echinodermata*, by cystoids; the *Cœlenterata*, by graptolites, medusæ, and corals; the *Porifera*, by

sponges, and the *Protozoa*, by rhizopods. This is a fine an
first appearance. As we come to study the representatives
detail, the breadth of the divergence, and the advance in
that had already taken place, will appear still more impressive
representatives are all marine forms. Of land animals ther
traces; but this negative record does not warrant the assertio
land animals lived at this time. Terrestrial arthropods, in th
scorpions and insects, appear in the record two periods later (
and they were then rather highly developed, which renders an
reaching back as far as the Cambrian, or beyond, not im
though by no means certain.

No traces of vertebrates have yet been detected in the
beds, but as fish remains have been found in the rocks of the
period (Ordovician), it would be hazardous to assume that
aquatic vertebrates were not among the denizens of the
waters. There is no reason, however, to think that any of the
vertebrates were present.

The Cambrian Arthropoda.[1]—Of the four divisions of th
poda, insects, spiders, myriapods, and crustaceans, only the
been found in the Cambrian strata. Its representatives were
and entomostraceans.

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[1] The State and Government Reports are the chief media for the de
fossils. Many descriptions are also found in scientific journals, and in t
ings of scientific societies, and, more rarely, in private memoirs. The lite
that on stratigraphy, is very voluminous, and cannot be fully cited in
this kind. A convenient key to most of the recent literature is found
Bibliography and Index of North American Geology, Paleontology, Pet
Mineralogy for 1892–1903, Bulls. 188, 189, 203, and 221, U. S. Geol. Surv.,
probably be carried to later dates. References to earlier descriptions wi
in Bull. 127, U. S. Geol. Surv.

Some of the leading writers on American Cambrian fossils are: James
N. Y., Vol. I, 1847, and Ann. Repts. N. Y., 1847–1863—notably the 16
ings, Paleozoic Fossils, Geol. Surv. of Canada, 1874; J. W. Salter, Quar.
Soc., 1859; S. W. Ford, Am. Jour. Sci., 1871–1881; R. P. Whitfield, N.
Surv. of 40th Parallel, and Wis. Repts., 1873–1879; C. Rominger, Proc.
Sci., 1887; J. F. Whiteaves, Am. Jour. Sci., 1878, and Canadian Rec. Sci.,
Foerste, Bull. Mus. Comp. Zool., Cambridge, 1888, and Am. Jour. Sci.,
Matthew, Trans. Roy. Soc. Canada, 1897–1900, Trans. N. Y. Acad. Sci., 18
Nat. Hist. Soc. New Brunswick, 1893–1902, and Canadian Rec. Sci., 1889
notably, C. D. Walcott, Bulls. 10, 30, and 81, U. S. Geol. Surv., 10th Ann.
Geol. Surv., Am. Jour. Sci., 1887–88, and Proc. U. S. National Museum, Vol
The identifications of Walcott are chiefly followed in this work.

The ***trilobites*** were easily the most distinguished of the known denizens of the Cambrian seas. They were not only the highest in organization, but the most characteristic of the age. Their successive genera best distinguish the successive stages of the period, and their distribution is a chief means of correlating the formations on different continents and in different provinces of the same continent, as previously set forth (p. 240). They have hence a leading place in historical and geological importance. They belonged to a race long since extinct. A study of the accompanying illustrations (Fig. 118) will best impress their distinguishing features, notably their three longitudinal lobes, whence their name, and their three transverse divisions, head, thorax,

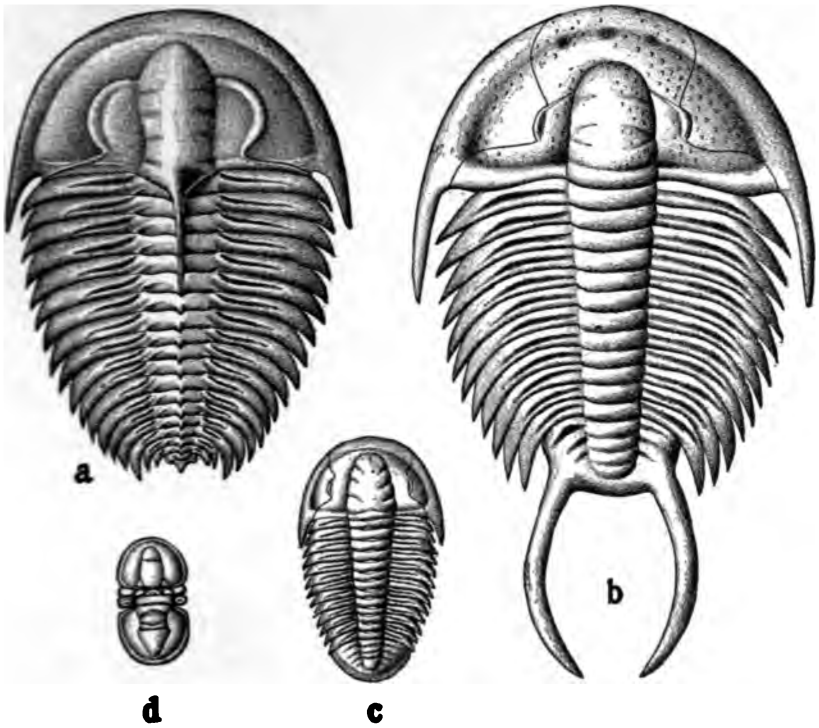

FIG. 118.—Cambrian Trilobites. *a, Holmia (Olenellus) bröggeri* Walcott, a characteristic trilobite of the Lower Cambrian; *b, Crepicephalus texanus* (Shumard), a trilobite of the Middle Cambrian; *c, Ptycoparia antiqua* (Salter), a trilobite of the Middle Cambrian. The above trilobites belong to the order *Opisthoparia*. *d. Agnostus obtusilobus* Matthew, a Middle Cambrian trilobite of the lowest order, *Hypoparia*, showing primitive characters, as the absence of eyes, small number of thoracic segments, etc.

and pygidium, or caudal shield. The variations of thes
and of the other parts of their structure furnish the basis
genera and species are founded. As the fleshy parts and th
understructure are wanting, the descriptions and identifi
species and genera are based solely on these harder parts
not exceptional. The determination of most fossil specie
such imperfect knowledge of the real organism, but the in
of knowledge is being gradually reduced by the finding of
preserve what is lacking in those previously found. Mu
value of these, and all other fossils, in the correlation of
in different regions, and in determining the succession of
not superposed, depends on the sharp discrimination of th
ences of form and structure, and a critical study of the figure
mended. In a work of this kind it is impracticable to
the special description of fossils; that is the function of pal
but some special attention may be given to these first forms,
in the great procession of life, so far as we know it.

The general aspect of the trilobites at once discloses an
development. It seems clear that they possessed nearl
anatomical systems and physiological functions of modern c
of their kind. In their line, they were much nearer the pres
the series than the theoretical beginning. Perhaps the ey
best index of their development. These show that the
system of fixed eyes, composed of many eyelets, was al
developed. In the trilobites of this and succeeding periods,
range from a score to several thousands. Some of the Cam
bites however had no eyes, never having acquired them, w
possessed abortive rudiments of eyes, implying that their
had possessed eyes, but had lost them. The acquisition an
of so important an organ seems to imply variation in the co
life, but this may mean no more than migration to deep da
or the habit of burrowing in the mud, where eyes became use
eyes were often slightly raised on crescentic lobes, with t
face outwards. In later epochs, these crescents became
more curved, extending the sweep of vision fore and aft to the
obvious advantage, and hence this became a mark of progres
Cambrian faunas, the segments of the body were rather sti
to one another, but in later epochs they became more flexible

trilobites rolled themselves up armadillo fashion—another mark of progress. The upper surface of the body was, even in Cambrian times, ornamented variously with granules, spines, and other markings, the significance of which is little understood. These ornamentations varied as time went on, increasing, in general, until after the climax of the trilobites had been passed.

The understructure is not revealed in the Cambrian specimens, the parts having been lost in fossilization, but later forms, worked out by Walcott, Beecher, and others, show that the trilobites possessed a row of slender articulated limbs on either side, and also delicate filaments which served the function of respiratory organs. The nature of the limbs indicates that the trilobites both walked and swam. It is inferred that some were swift of movement, while the weakness of the ambulatory organs in others implies that they were slow. The trilobites also possessed antennæ which doubtless served as organs of touch—another indication of the definite development of the senses, even at this early time. It is interesting to note that the habit of moulting the shell at successive stages of growth had been acquired. Leaving further details to the special study of the accompanying figures, it is to be observed that, at this early day, there had been acquired a highly complex, well-differentiated organization, endowed with nearly all the organs and functions possessed by similar crustaceans of the present day.

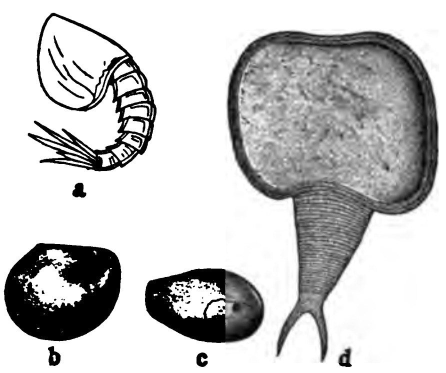

FIG. 119.—Other Cambrian Crustacea. *a*, *Hymenocaris vermicauda* Salter; *b*, *Aristozoe rotundata* Walcott, a Cambrian phyllocarid; *c*, *Leperditia dermatoides* Walcott, a Cambrian ostracode; *d*, *Protocaris marshi* Walcott, a Cambrian phyllopod.

Besides these ancestral crustaceans, a few other forms of interest were present, among which were little ostracodes which had valve-like shells on their backs much like those of bivalve mollusks (Fig. 119, *c*), an ancient type of phyllopods represented by the singular form *Protocaris* (Fig. 119, *d*), and a phyllocarid (Fig. 119, *a* and *b*).

The Cambrian Mollusca.—A few cephalopods (chambered shells) which are regarded as the highest class of mollusks have been the uppermost beds referred to the Cambrian, but none as y lower part. As the cephalopods were even then highly d structurally, and were widely differentiated from the other there is little ground to doubt that they had already passed t long period of development, and hence that they were really p some part of the globe during the earlier Cambrian time remains are so rare that they have little geologic importanc period, but become prominent in the next.

The pelecypods (bivalves) were represented in the Lower beds, though they have not been found abundantly. Whe implies that they did not live abundantly in the seas that deposits that are now accessible, or that they were but poorly p is not known. Fig. 120, *b*, represents a typical form.

Gastropods (univalves) (Fig. 120, *c*, *d*, and *e*) were somewh dant even in the earlier Cambrian times, and became more

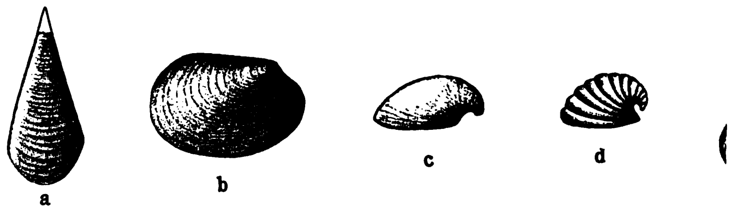

FIG. 120.—Cambrian Mollusca. *a*, *Hyolithes americanus* Billings, a pter Lower Cambrian; *b*, *Fordilla troyensis* Barrande, a pelecypod of Cambrian; *c*, *Stenotheca rugosa*, var. *paupera* Billings, *d*, *S. rugosa* H gastropods of the Lower Cambrian; *e*, *Trochus saratogensis* Walcott, gastropod with well-developed spire.

toward the close of the period. The early forms found are the low conical type, known as capulids, from their resembla form of cap typified by the conventional "liberty-cap" (see F in particular). The more amply coiled and spiral forms (Fi though present, only became common later. The close resem *Trochus saratogensis* (Fig. 120, *e*) and other forms to modern g is worthy of note as showing how near to the present de some of the Cambrian mollusks had attained.

The Cambrian Molluscoidea.—This branch was well repre brachiopods (lamp-shells), (Fig. 121). In geological importa rank second only to the trilobites in Cambrian times. U trilobites, which became extinct at an early day, the brachiopods have persisted to the present time, and stand as a foremost representative of extreme stability and persistence. They have changed in species and, except in a few cases, in genera also, but the class has been only slightly modified and still retains, with great fidelity, its distinctive characteristics.

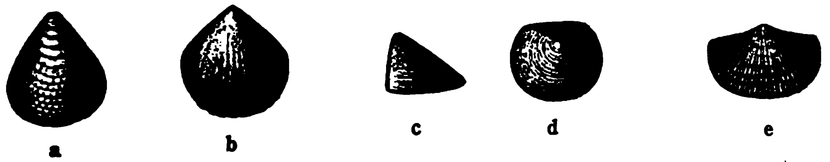

Fig. 121.—Cambrian Brachiopoda. *a*, *Obolella gemma* Billings; *b*, *Protorhyncha antiquata* Billings, brachiopods of the Lower Cambrian; *c* and *d*, *Acrotreta gemma* Billings, a brachiopod ranging from the Lower to the Upper Cambrian, summit and side views of the pedicle or ventral valve; *e*, *Billingsella transversa* Walcott, the pedicle or ventral valve of a hinged brachiopod of the Lower Cambrian.

In Cambrian times, as now, the valves of one division of the group were hinged, while those of another were not. So, too, then as now, one division formed shells of calcium phosphate, and another shells of calcium carbonate. Comparisons in other respects show that the changes between the Cambrian and the present are but a small fraction of the

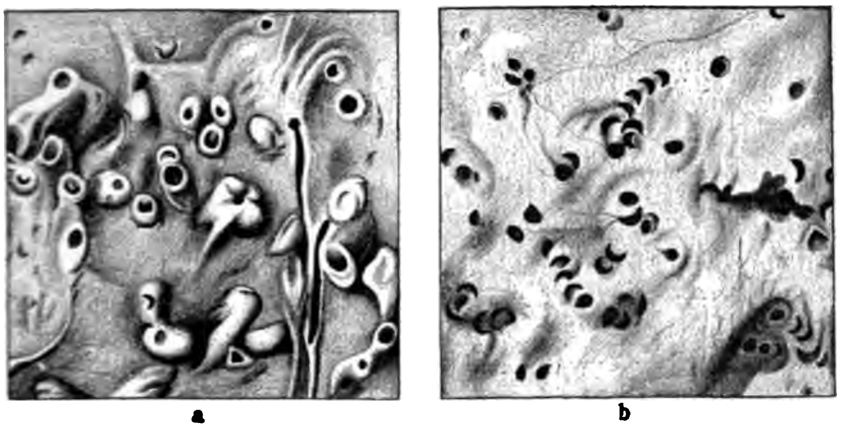

Fig. 122.—Cambrian Vermes; borings and trails. *a*, a natural surface of sandstone seen from above, showing annelid borings, with mounds of sand heaped about their mouths and with trails leading away from some of them; *b*, a horizontal section, showing perfect borings, as well as abandoned borings whose sides have been forced in during the formation of new borings, giving a crescentic cross-section. Although the animal is not shown, the name *Arenicolites woodi* Whitfield is assigned to it.

changes involved in the development of the brachiopods f theoretical primitive forms in pre-Cambrian times. Though tl iopods were wonderfully persistent and conservative in evolut were undergoing changes from epoch to epoch, and thus they valuable indices of progress, and serviceable means of identify zons and correlating distinct deposits.

The Cambrian Vermes.—Sea worms, or annelids, left indic their abundant presence by borings and tracks, and occasio mud or sand heapings at the mouths of their holes (Fig. 122) remains of the animals themselves have been found.

The Cambrian Echinodermata.—A few cystids were prese 123). They had roundish or cylindrical bodies, covered un rically with plates. Irreg were attached to the up and a stem, often short an plete, was appended to t end. The cystids were t runners of the beautiful (stone lilies) which perha into existence during the C times, but have not yet be in fossil form.

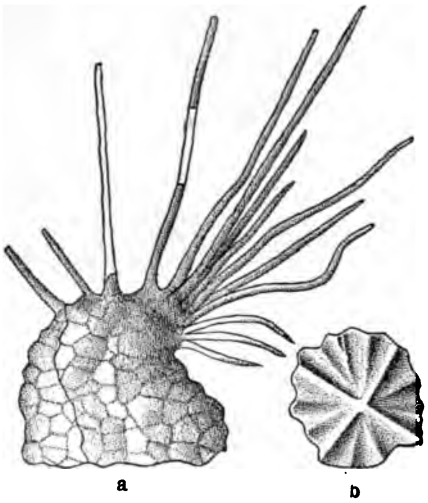

FIG. 123.—Cambrian Echinodermata. *a*, *Eocystites* (?) *longidactylus* Walcott, a view of the upper part of an imperfect Cambrian cystid, showing the irregular plates and broken arms; *b*, *Eocystites primævous* Billings, a single cystidian plate.

The Cambrian Cœlen The cœlenterates were rep by *hydrozoa* (graptolites dusæ) and by *anthozoa* (cor 124). The eccentric and a explicable freaks of fossiliz nowhere better illustrated the Cambrian relics of th Graptolites, although an most delicate of animal fo medusæ, among the softest of animals, were preserved, while m robust and indurated forms, that almost certainly were pre scant relics, or none at all. The graptolites, an extinct group, slender, plume-like organisms, consisting of a series of cells, the individual animal lived, attached to a common slender a united the colony and which often branched much after the f plants. The whole plume appears to have floated free in the sea. They were scantily preserved in the earliest Cambrian (Fig. 124, *e*), but quite abundantly toward its close. The secret of their preservation probably lies in the fact that, being floating forms, they most often settled in quiet and rather deep waters off-shore, where very fine silts accumulated, and where, therefore, the conditions were favorable for burial without destructive action.

The most singular case of fossilization is the preservation of traces of jelly-fish, or at least of what are so identified. These are illustrated in Fig. 124, *c* and *d*. Their impressions are found in the lower division of the Cambrian.

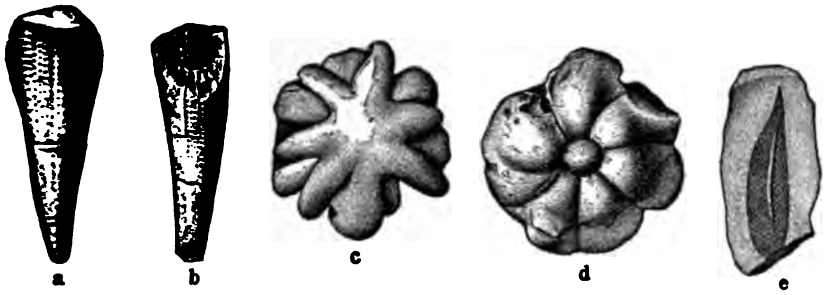

FIG. 124.—Cambrian Cœlenterata; supposed corals, medusæ, and graptolites. *a* and *b*, *Archæocyathus rensselæricus* Ford, a problematic fossil referred by some paleontologists to sponges, and by others to corals; *c* and *d*, *Brooksella alternata* Walcott, supposed casts of the gastric cavities of medusæ; *c*, a supposed exumbrella in which the interumbrella lobes are a prominent feature; *d*, a view of a supposed umbrella with six lobes and a depression over the central stomach; *e*, *Phyllograptus* (?) *cambrensis* Walcott, the hydrosoma of a graptolite.

Obscure forms of corals were also present (Fig. 124, *a* and *b*) though none of the higher types has yet been discovered. The forms found resemble sponges so much that they were long regarded as such, but recent microscopical examination by Hinde seems to show that they had a coralline nature.

True sponges were present in some abundance and ranged throughout the period. Their spicules have been sometimes found where the general form and the fibrous parts have perished.

The Cambrian Protozoa.—It is probable that many of the low simple forms classed as protozoans were present, but owing to their unsuitability to preservation as fossils, only a few identifiable forms have been found.[1]

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[1] Several are described by G. F. Matthew in "The Protelenus Fauna," Trans. N. Y. Acad. Sci., Vol. XIV, 1895, pp. 101-153.

Unidentified forms.—Besides the forms that can be there are some which cannot be interpreted with certainty these are certain tracks found in Canada, Wisconsin, and Two varieties are illustrated in Fig. 125. They consist of c rows of V-like forms with trail markings superposed, as th ments or flexible organs were dragged over the impressio diately after they were formed. The organs that made t impressions were flexible, as shown by the variation in th

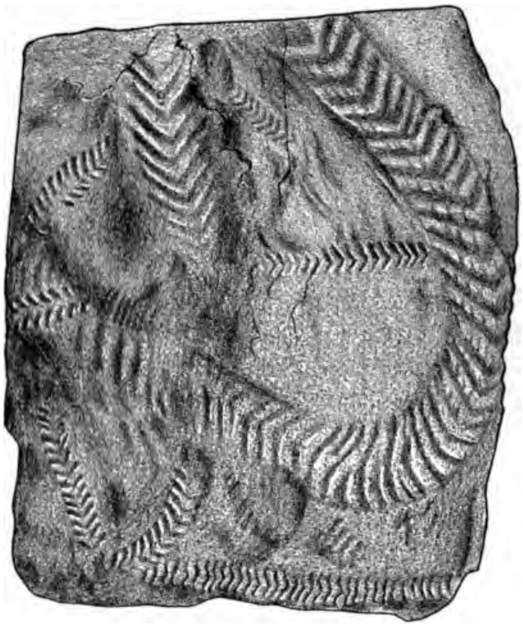

FIG. 125.—Unidentified forms. Tracks of an unknown animal found in Cambrian sandstone near New Lisbon, Wis.

the tracks, the curvature of the ridges, and the shifting of tion of the apex. The depth of the impressions and the c of the surface of the sand implies a rather heavy animal, or burrowed beneath the sand. The nature of the animal that them is problematical. There are other impressions that rows of indentations, as though made by the feet of arthrop still others are continuous grooves.

Implied life.—Scientific geology, in the strict sense of contents itself with considering the demonstrable forms immediate indications, but philosophical geology goes further and endeavors to supply such forms as may be necessary to fill out a consistent assemblage of life. It has already been noted that the presence of so much animal life implies much vegetable life to supply the necessary food. This inference is almost as firm as the inference that the fossils really represent organisms that once lived, which was once questioned, but is now regarded as a scientific conclusion. Firm inferences, like that of the presence of abundant vegetation in the Cambrian, grade away insensibly into others that are weaker and weaker until they become very infirm. There is hence a danger of extending philosophical geology until it shall pass into speculative geology, without being fully aware of the fact. Great circumspection is needed when the field of free inference is invaded, but the subject of ancient life would be left barren of half its interest, and most of its stimulus, if inferences were not indulged in their proper places and to their proper degrees. The need of caution arises more largely perhaps from unrecognized alternatives than from any other single source. For example, in the inference relative to vegetation in the Cambrian and pre-Cambrian times, which seems so imperative, it is barely possible that an early form of life intermediate between plants and animals, or combining their qualities, and ancestral to both, may have lived in the earliest ages, and have possessed the power of organizing organic matter from inorganic matter. These may have furnished the ulterior food of the animals, instead of plants, which may have been differentiated from them later. And so even the strong case of inferring vegetation from the presence of animals is not without some small occasion for reserve. But this is really only a change in the form of the inference rather than in its real substance, which is that Cambrian animals imply the existence of plants or of unknown organisms that performed the chemical functions now performed by plants.

Duly mindful of the weaknesses and dangers of pressing inferences too far and duly appreciative of their stimulative value when properly controlled, we may inquire how far the forms and functions of the known Cambrian animals suggest the existence of other animals whose presence is not recorded. A large percentage of the known Cambrian animals were provided with shells, tests, plates, or other forms of hard coverings. In the main these appear to have been protective devices, and imply enemies or combative rivals against which the

protection was needed. Can the known Cambrian animals
stituted such enemies, or must others be supposed to ha
to furnish a good reason for such protective provisions? Pe
most significant feature of the protective devices lies in the
they are usually of the same type as those possessed by
sponding animals of later times. The shells of the gastropo
pods, and brachiopods differ from those of to-day only in
tures. The coverings of the trilobites are very much the
those of their crustacean relatives in existing seas. Much
may be said of nearly every form. If there had been a radi
in the character of their enemies or rivals, we might expect s
ble change in the defensive devices. It is a natural infere
fore, that the conflicts of life in the Cambrian waters had be
much what they have been in later times. The inferenc
pushed a step further, and the deduction drawn that th
which led to the evolution of the defensive devices were
same that they have been throughout the period of their
If the reign of the great predaceous mollusks, the cephal
that of the predaceous fishes be supposed to have reached ba
the Cambrian period to the time when the armorings of t
forms were acquired, the total assemblage of attackers and
in the seas would have been very much the same as it is n
marine reptiles and mammals that have come in since have
tially changed the nature of the conflict. The occurrence o
alopods in the closing stage of the Cambrian, and of the fi
succeeding Ordovician period, removes any special im
from the hypothesis that they were present in the early
and perhaps even earlier.

If the defensive devices of the Cambrian animals are to b
within the strict limits of the known forms, the armor o
trilobites must apparently be regarded as a defense aga
bers of their own race, for no other known animal appa
sufficient celerity of motion and sufficient strength to giv
for such protection. A similar remark may be made of
cephalopods when they came in toward the close of the pe
protection of the gastropods, pelecypods, brachiopods, e
early Cambrian may have been needed as a defense agains
bites, but it is not at all clear that just such coverings a

were specially adapted to defend them against the trilobites, as we should expect them to be if evolved for this special purpose.

While final conclusions can scarcely be reached by such studies, they lend interest to the study of the parts which are chiefly fossilized and throw a little light on the life of these early inhabitants of the globe.

Sociological development.—If sociology be defined as the relationship of one living thing to others, the relations of attack and defense may be said to constitute the militant phase of the sociological development of the Cambrian times. These beginnings of animal sociology possess no small interest and importance, however crude they may seem to be, if we entertain the doctrine of evolution in its broader phases which embrace mental as well as physical evolution. The adjustment of the organisms to one another and the development of qualities, physical and mental, suited to such adjustment, is a subject applicable to all the ages in which conscious life prevailed, and the simple lessons of its crude beginning may not be less instructive than the more intricate ones of the late stages. The early evidence, to be sure, is imperfect, and the interpretation is by no means sure, but it nevertheless merits attention.

The shells of trilobites are sometimes found together in large numbers. Occasionally they are closely packed, "spoon-fashion." Not unlikely these may be the molted shells, for the habit of molting had been acquired even at this time. Possibly the assembling of the shells may be the work of currents or similar inorganic agencies, but the suggestion that the trilobites were gregarious, either habitually or seasonally, may be entertained. Obscure and uncertain as these and similar suggestions may be, we shall not have followed the history of life development far before the evidences of social relations will be distinct and unmistakable.

Mental development.—The wars of the Cambrian inhabitants, implied by their weapons of offense and defense, can scarcely have been unaccompanied by some notable measure of mental development, however the nature of such development may be interpreted. That the trilobites sought their food or pursued their prey by sight, and were guided by touch, their eyes and their antennæ imply, and it is difficult to conceive of these actions without the mental processes that usually attended on pursuit and capture. The control of so complex and active an organism as that of the trilobite implies an development of the nervous system. It is not safe to at say how far this admirable mechanism was directed by conscio gence, as distinguished from what we choose to call automatic c tive action, but there is food for thought in placing ourselv face with the alternative of either assigning these fine orgar their complex activities to unconscious automatism, or else of ing in them the early stages of conscious psychology. Wh interpretations be wholly correct or not, it is better to give thought to these higher problems than to ignore one of the 1 phases of life-evolution.

Ecological adaptations.—A study of the distribution of brian fossils gives indications that then, as ever since, ther adaptation of life to its immediate physical environment. appears to have varied with the nature of the bottom, with of the water, and with other marine conditions, much as it do There were mud-bottom faunas, sand-bottom faunas, and lik tions. There seem to have been zones of shore life (littora shore life (photobathic), and of deep-sea life (pelagic and although the evidence of the last is scant. It is important nize these variations in the comparison and correlation of f considerable differences may occur among faunas which we contemporaneous. Except in the case of floating forms, relatively indifferent to the bottom, it is usually possible tc the nature of the conditions under which the animals lived nature of the sediments in which the fossils are imbedded.

Zoölogical provinces.—The assemblages of the life of t seem to have varied in a broader way, giving rise to zoölogical The leading agents in developing these provinces were probab that isolated certain portions of the sea from other porti isolation was not complete in most cases, but reached such of separation as to cause the life of each area to develop alo lines, in more or less independence of the evolution of oth The leading principles involved have been set forth in Volume 672, particularly in that portion which relates to provincial mopolitan evolution, pp. 668–672.

The early faunas of the Cambrian were somewhat pro nature, though the provinces appear to have been large.

e close of the period, as the seas crept out upon the face of the con- ents, there was a marked tendency toward cosmopolitanism. The pression that life was everywhere the same at a given stage in the rly ages, which naturally arises from the very general and limited eatment of the faunas to which works of this kind are confined by eir limitations of space, is to be guarded against. There was prob- bly less variation in the life of the different regions, during most of e geological epochs, than there is to-day, but it is not certain that is was true of all past epochs, and in none of them was there prob- bly anything like complete uniformity over the whole globe, though ere was, at times, much tendency in that direction, as implied by e term cosmopolitanism.

Comparison of pre-Cambrian and post-Cambrian evolution.—After his summary review of the Cambrian life, it is appropriate to return o the question raised at the outset relative to the degree of develop- ent which this first well-preserved fauna exhibits. On the anatomi- al and physiological side, it is clear that nearly or quite all the funda- ental organs had been developed. There were skeletal systems f several forms; there were muscular systems, as shown by the impres- ions and protrusions on shells and as implied by the articulate struc- ure of the trilobites; there were nervous systems, as implied by eyes nd other evidences of sense-organs, and by the need for muscular ontrol; there were organs for capturing and ingesting food, and ence, almost certainly, organs of digestion, secretion, excretion, and espiration; in short, there were practically all the great anatomical nd physiological systems now possessed by animals. The Cambrian nimals had acquired the various modes of life possessed by existing nimals of their kind, as well as the various modes of preserving their ives. It is probable that all, or nearly all, the senses had some develop- ent, though this cannot be proved for certain senses. The eyes of he trilobite show that that wonderful organ was already developed n a notable degree.

In the evaluation of these evolutions it is not to be overlooked that he *initiation* of all these structures and functions is involved.

In the matter of the divergence and the isolation of classes, and he establishment of type forms, it is to be again noted that not only ere all the animal subkingdoms, save perhaps the vertebrate, pres- nt, but that, in many of them, the forms had come to have so nearly

the aspect of present forms that the classes and some orders a
recognized.

The concrete question then arises, How does the initi
the divergence of the structures and of the types that pre
Cambrian stage compare with the developments since? Th
given by expert students of life-development very naturally
so far as known to us, they all assign a decidedly greater va
pre-Cambrian than to the post-Cambrian evolution. Form
numerical terms, from sixty to ninety per cent. of the whole
is attributed to pre-Cambrian times.

The Succession of Faunas.

Under the doctrine of evolution, it is presumed that t
every past stage has grown out of that which immediately
it, and that it has merged into that which immediately f
It is usually assumed that if no exceptional influences af
process, there was a continuous series of slow changes with
lines of demarkation. If this conception were realized in fact
be less appropriate to speak of a succession of faunas than o
tinuous ever-changing fauna. It is not yet demonstrated,
that evolution proceeded solely by very slight changes comi
generation to generation. A doctrine of evolution by di
abrupt mutations has recently been advanced by DeVr
maintains that changes as great as those usually regarded as d
ing species may take place between parent and offspring,
the new characters so introduced may be perpetuated a
permanent. This is equivalent to maintaining that new s
arise abruptly when the parent form is in what is termed
ting stage. It is not held that these changes take place in
at all stages, but only in some species at certain periods of t
ence when they are in this mutating condition. The d
at present held, does not maintain that a whole fauna woul
to change into a different fauna abruptly, but merely that n
might arise in it abruptly. At present the doctrine rests
observations and experiments made on a few plants. I

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[1] Die Mutationstheorie, 1903. See also Bateson's Materials for the St
tion, 1894; and W. B. Scott, On Variations and Mutations, Am. Jour.
355.

for more extensive experimental studies to substantiate or overthrow this most important doctrine. While awaiting the fate of this and cognate biological doctrines, it is to be noted that the geological record, as now known, does not show a complete gradation from one species into another, though this may be due, as commonly assigned, to the imperfection of the record. In some cases there is a close approximation to a graded series from one species to another, but the steps of the gradation are not sufficiently close and definite to decide between evolution by an infinite number of small changes, and a more abrupt change, masked more or less by variations, as postulated by the mutation theory.

If we turn from species to faunas, which embrace a large number of species belonging to quite different orders, it is obvious that a more general point of view must be taken, and that inferences connected with biological and physical environment, such as set forth in Volume I, pp. 663–672, are to be brought under study. As a matter of observation, it appears that sometimes one fauna graduates into the succeeding one, while at other times the change is apparently abrupt. If the progress of life the world over could be studied as a unit, it would probably appear that there was a nearly perfect gradation of the life of one stage into that of the next. This gradation probably took place more rapidly at some times than at others, and it is quite certain that some forms changed much more rapidly than others. But when we limit our study to the succession of life of any one continent, or to that of its coasts or embayments, or to that of some one of the seas on its borders or on its bosom, or to that of any limited province, it is evident that the progress of evolution in the given region was subjected to interruption by physical changes, such as affected the depth, temperature, or clarity of the water, the nature of the bottom and like elements of the local environment, and that these brought about shiftings in the distribution of life. Out of these local influences superposed on the general progress of life there grew rather definite stages of change between which the faunas retained a rather constant and distinctive aspect, though always undergoing some modification. Where the change is found to have been abrupt and there is no evidence of a break in the record, the explanation is usually to be sought in migration, by which a new fauna came in from somewhere else and the old fauna emigrated to a new field, or was overwhelmed by the invaders. Comparatively slight changes in the relations o land were competent to introduce or to remove barriers and mit such migratory movements (see pp. 668–672, Vol. I). T process is closely analogous to the well-known succession of th races that has been brought about by the migrations of ma Old and New Worlds.

Pondering upon these agencies, it becomes clear that in t of faunal progress there is occasion to recognize (1) rathe changes brought about by overwhelming invasions; (2) les changes brought about by the more gradual inflow of foreign and the gradual commingling of the immigrants with the species; (3) very gradual changes, or nearly constant states the slow evolution of resident species when not much affected gration or by physical changes; and (4) more rapid evolutio profound changes in the physical conditions or in other agenci ing the life, including perhaps the unknown causes that n brought about a mutating stage simultaneously in large nu the leading species.

The greatest of the faunal changes are those that mark of "Eras" and of the greater "Periods" (using these terms in t nical senses); but within the "Periods" there were less radica that marked off the lesser successions of the faunas. Within brian period, three stages in the life progress are recognized are made the ground for distinguishing the Lower (or *Olene* Middle (or *Paradoxides*), and the Upper (or *Dikellocephalus*) the period. It is to be understood that there were not a fe which lived from one stage into the next and constituted bonds the faunas, and that the demarkation is not very distinct, were leading forms that were confined to the individual st characterized them and their faunas.

The Lower Cambrian or Olenellus fauna.[1]—The most characteristi the lower fauna is the *Olenellus*, a finely developed trilobite of w types are illustrated herewith, *Olenellus gilberti* (Fig. 126, *b*), *Holmia bröggeri* (Fig. 118, *a*), and *Mesonacis* (*Olenellus*) *vermontana* (Fig. 12

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[1] See The Fauna of the Lower Cambrian or Olenellus Zone, by Chas. Tenth Ann. Rept., U. S. Geol. Surv., 1888–89, and the papers therein Mr. G. F. Matthew, who has given much study to the Cambrian faunas o dian provinces, interprets the succession somewhat differently from Walc here followed. See Matthew's papers referred to in foot-note, p. 280.

of these were formerly placed under the genus *Olenellus*, but the last two are now generally recognized as separate genera, and are highly characteristic of the Lower Cambrian horizons. *Holmia* is found in the coast province, and in Europe, notably in Sweden; it occurs rarely in the Appalachian province. *Mesonacis* is found in both the Appalachian and coast tracts. *Olenellus gilberti* (Fig. 126) is a typical form found in the western provinces. *O. Thompsoni* occurs in the Appalachian tract. The lowest order of trilobites (the *Hypoparia*) is represented by *Microdiscus speciosus* (Fig. 126, *c*). Its primitive characters are shown in the apparent absence of eyes, the small number of thoracic segments, and its similarity to the early stages of the higher trilobites. At least fifteen genera of trilobites, represented by fifty species, have already been found in the Lower Cambrian of America. Of brachiopods at least ten genera and thirty species are known, and many more will doubtless be found. Among the characteristic forms are *Kutorgina cingulata* (Figs. 126, *d* and *e*), *Iphidea labradorica var. swantonensis* (Figs. 126, *f* and *g*), *Protorhyncha antiquata* (Fig. 121, *b*), *Obolella gemma* (Fig. 121, *a*), *Billingsella transversa* (Fig. 121, *e*) and *Acrotreta gemma* (Fig. 121, *c* and *d*), and *Lingulella cœlata* (Fig. 126, *i*). Of gastropods, at least a half-dozen genera and a dozen species are known, among which were *Stenotheca rugosa* (Fig. 120, *c* and *d*), and *Platyceras primævum* (Fig. 126, *h*), characteristic forms. Among the typical pelecypods was *Fordilla troyensis* (Fig. 120, *b*). A quite common

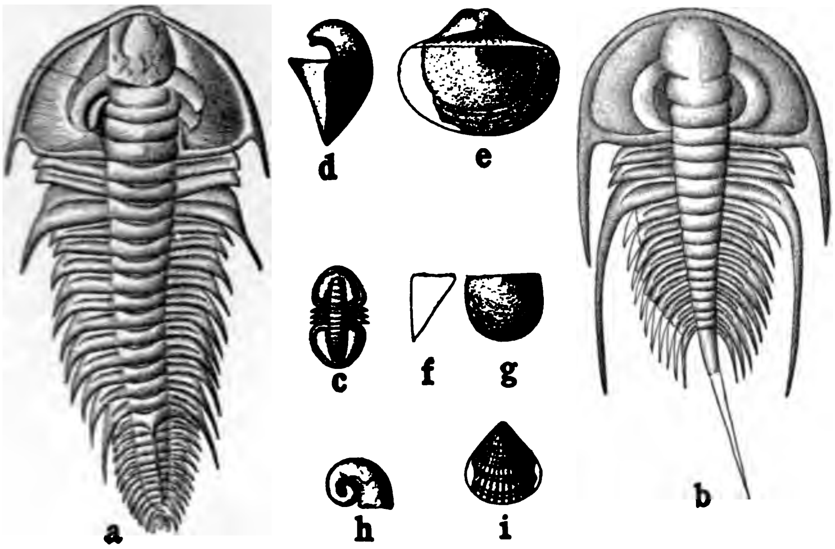

FIG. 126.—Lower Cambrian Fossils. *Trilobites: a*, *Mesonacis* (*Olenellus*) *vermontana* Hall; *b*, *Olenellus gilberti* Meek; *c*, *Microdiscus speciosus* Ford; *Brachiopods: d* and *e*, *Kutorgina cingulata* Billings, side and dorsal or brachial views; *f* and *g*, *Iphidea labradorica*, var. *swansonensis* Walcott, dorsal or brachial valve and cross-section; *i*, *Lingulella cælata* Hall; *Gastropod: h*, *Platyceras primævum* Billings.

fossil all through the Cambrian was the *Hyolithes*, usually referred to
pods. *H. americanus* (Fig. 120, *a*) was one of many Lower Cambria

There were forms usually referred to sponges, but identified by
corals, such as *Archæocyathus rensselæricus* (Fig. 124, *a* and *b*) and
such as *Phyllograptus cambrensis* (Fig. 124, *e*). Fig. 124, *c* and *d*,
alternata, represent a series of singular forms regarded by Nathorst a
as the casts of the gastric cavity of a medusa.[1] There were worm-borin
and unidentifiable forms, making up, altogether, a rather varied fauna

The Middle Cambrian or Paradoxides fauna.—The general aspect of
of the Middle Cambrian was similar to that of the lower division. The

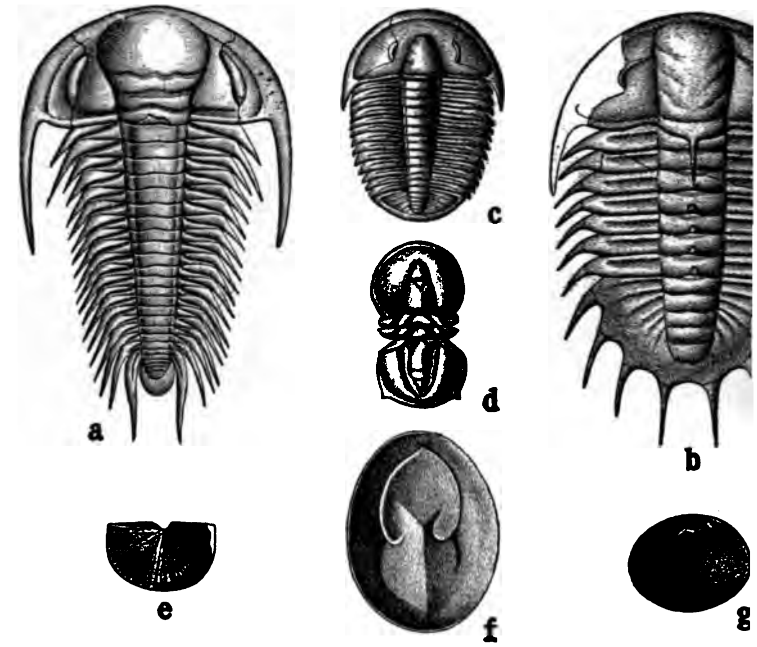

FIG. 127.—Middle Cambrian Fossils. *Trilobites: a, Paradoxides bohemi*
b, Olenoides curticei Walcott; *c, Ptychoparia kingi* Meek; *d, Agnostus*
White; *Brachiopods: e, Protorthis billingsi* (Hartt); *g, Linnarsonia*
(Hartt); *Gastropods: f, Harttia matthewi* Walcott, interior of the s

slight evidence of advance in organization, and as knowledge now
increase in numbers, but apparently a decline, which is probably mere
of the record. The *Olenellus* had disappeared and the *Paradoxides* (F
reigned in its stead. The trilobites appear to have reached their clin
in certain species of the *Paradoxides*, some individuals attaining a l
foot and a half, but there was further advance in structure and numl

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[1] For a special discussion and numerous illustrations of these forms,
Medusæ, Mono. XXX, U. S. Geol. Surv., 1898, by Walcott.

succeeding epochs. *Crepicephalus texanus* (Fig. 118, *b*) and *Olenoides curticei* (Fig. 127, *b*) are interesting trilobites belonging to the middle fauna. *Ptychoparia kingi* (Fig. 127, *c*) and *P. antiqua* (Fig. 118, *c*) are species characteristic of the middle stage, but the genus ranges both below and above. *Agnostus interstrictus* (Fig. 127, *d*) and *A. obtusilobus* (Fig. 118, *d*) represent the lowest type of trilobites. Brachiopods, as before, were next to the trilobites in importance. *Protorthis billingsi* (Fig. 127, *e*) and *Linnarssonia transversa* (Fig. 127, *g*) are distinguishing species. *Acrotreta gemma* (Fig. 121, *c* and *d*) and some other species of the lower fauna lived through the middle and into the upper stage. *Harttia matthewi* (Fig. 127, *f*) represents an interesting gastropod of the time. *Hyolithes*, representing the pteropods, were common; other pteropods were few. Plates of cystidians (*Eocystites primævus*, Fig. 123) have been found, but no complete forms.

The fauna as here characterized is that which prevailed in the Atlantic province. In the interior and western province, no very distinct Middle Cambrian fauna has been detected and the life of that stage does not seem to have closely corresponded to that of the Atlantic province.

The Upper Cambrian or Dikellocephalus fauna.—The most characteristic trilobite of the Upper Cambrian of America is the *Dikellocephalus*, while in Europe it is *Olenus*, though *Dikellocephalus* occurs there. The *D. pepinensis* (Fig. 128, *a*) is a typical species. There were many smaller trilobites, among which were species of *Ptychoparia*, *Conocoryphe*, *Crepicephalus*, *Agraulus*, etc. Brachiopods were well represented by phosphate linguloid shells, of which *Lingulepis pinniformis* (Fig. 128, *e* and *f*) and *Obolella polita* (Fig. 128, *g*) may be taken as typical, and by shells of calcium carbonate of which *Plectorthis newtonensis* (Fig. 128, *b* and *c*) and *Billingsella coloradoensis* (Fig. 128, *m* and *n*) are examples. The *Hyolithes* (Fig. 128, *d*) were still common. Gastropods were abundant in favorable localities, and were represented by shells of the cap type, by those coiled into a spire, as *Holopea sweeti* (Fig. 128, *h*), by those coiled in a plane, as *Bellerophon antiquatus* (Fig. 128, *i* and *j*), and by those having a depressed coil, as *Ophileta primordialis* (Fig. 128, *k* and *l*). Pelecypods and cephalopods were rare; as were also corals and cystoids. Annelids are quite frequently represented by borings and occasionally by mounds heaped about the openings of these and by trails leading away from them, as shown in Fig. 122. Greensand (*Glauconite*, a silicate of potash and iron) is rather abundant in certain horizons of the Upper Cambrian. As much of the glauconite of later beds is associated with rhizopod shells, and is now forming in connection with them, the abundant presence of rhizopods in the Upper Cambrian is inferred. Near the summit of the Cambrian series, as it is usually defined, graptolites (Fig. 124, *c*) become abundant and wide-spread, and characterize a horizon known as the *Dictyonema* beds.

The foreign Cambrian faunas.—There is a rather close correspondence between the faunas of the eastern American province and those of the western and southern European provinces, which is but another way of saying that the faunas around the border of the North Atlantic were much alike. Those of the interior and western portion of appear to have been more nearly correlated with the faunas of and eastern Eurasia. Richthofen found typical Cambrian fc eastern China, and his observations have been confirmed and e recently by Willis and Blackwelder. Fossils of the Cambrian but somewhat divergent from the European types, occur in t

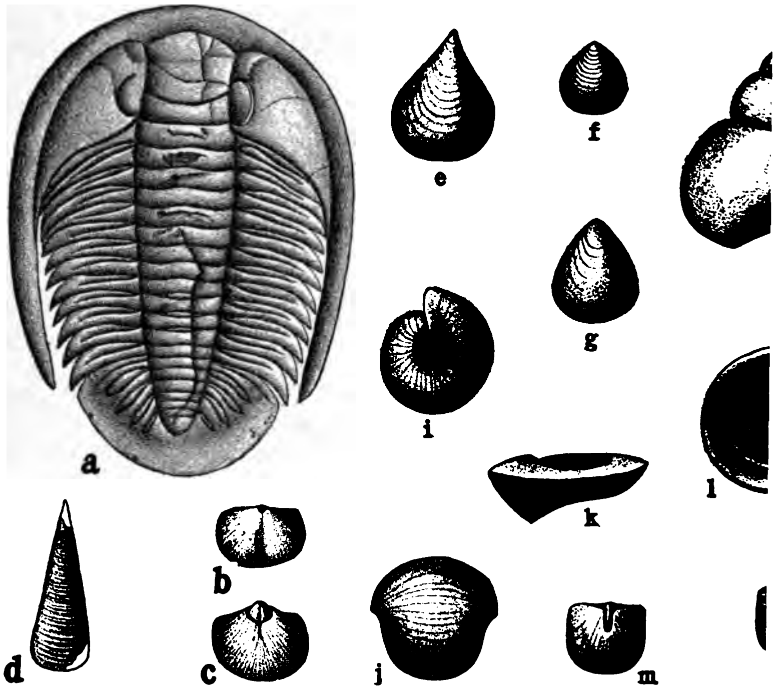

FIG. 128.—Upper Cambrian Fossils. *Trilobites:* *a*, *Dikellocephalus pepinen* *Brachiopods:* *b* and *c*, *Plectorthis newtonensis* Weller, internal casts of th or dorsal and pedicle or ventral valves; *e* and *f*, *Lingulepis pinniforn* views of the two valves; *g*, *Obolella polita* Hall; *m* and *n*, *Billingsella col* (Shum.). *Gastropods:* *h*, *Holopea sweeti* Whitfield; *i* and *j*, *Bellerophon* Whitfield, two views of the same shell; *k* and *l*, *Ophileta primordalis* two views of the same shell. *Pteropod:* *d*, *Hyolithes*.

range of India, while more typical forms, embracing *Olene* *Dikellocephalus*, are found in south Australia and Tasmania. Th Cambrian fauna is found in northern Argentina. Taken al these facts show that the same general types of life prevailed out the world, so far as known, while there were notable p variations then, as at all later stages.

The abrupt appearance of the Cambrian fauna.—The explanation of the apparent suddenness of the appearance of the Cambrian fauna is one of the open questions of geology. In a general way, it may be said that the previous beds were subjected to distortion and metamorphism and that this was liable to destroy any fossils that might have been preserved; but this is not wholly satisfactory, for some of the earlier beds are not greatly changed, and seem quite capable of receiving and retaining organic impressions. In later formations that have been considerably disturbed and changed, fossils are sometimes retained. It is equally true that later beds that seem quite capable of receiving and retaining organic impressions are devoid of them. On the whole, geologists seem inclined to refer the scantiness of pre-Cambrian fossils, and hence the apparent abruptness of the introduction of the Cambrian fauna, to unfavorable conditions for fossilization, combined with subsequent changes in the rock. This makes the abruptness merely a matter of preservation, not of evolution or real introduction. Two suggestions have, however, been made which entertain the thought that the coming of the Cambrian life into the shallow seas about the continents, and the taking on of its characteristic forms, were really, in some measure, abrupt, though the general evolution of life elsewhere and under other conditions had long been in progress.

Brooks' hypothesis.—The first of these[1] postulates that the earlier forms of life originated in the surface-waters of the open ocean, as one-celled organisms, and that, because of the simple and monotonous conditions there prevalent, the pelagic plant life has remained simple and unicellular in the main to the present time and still constitutes the chief food of all marine animals. There was little occasion for unicellular organisms to develop into aggregated forms, for in the water separate cells had larger contact with the food-supplies and with the sunlight than aggregated cells. It was only when the life became attached to the bottom or shore, or crept out upon the land, that aggregation of cells and the development of complex organisms became a marked feature in evolution. At first the conditions were unfavorable for life-development on the land and on the sea-borders;

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[1] W. K. Brooks, The Origin of the Oldest Fossils and the Discovery of the Bottom of the Ocean, Jour. Geol., Vol. II, 1894, pp. 455–479. Some features have been here added to the hypothesis.

for under this hypothesis the land was still barren and its wat
wholly sterile so far as food for animals was concerned. Bes
account of the unprotected nature of the land surface, the w
unrestrained and the waters were doubtless uncommonly sil
a result, the sea waters about the borders of the land were
sterile and muddy, and hence uninviting to most marine
It was only as the plants spread to the shores and crept over
that the shore waters became clear and enriched in organic
When at length vegetation made the shores and shallow wat
genial homes for animals, they are thought to have plante
selves there and to have evolved types adapted to that envi
with relative rapidity.

The second hypothesis.—The other suggestion involves an
point of origin and an opposite direction of distribution. It
that the first forms of life were simple plants that originate
land waters. In this, appeal is made to the observation of
that the fresh-water plants are of more germinal and plasti
than the marine plants and are apparently better suited to diff
into the present rich and varied vegetable kingdom. They we
situated for this since the great differentiations of the vegeta
dom have taken place chiefly on the land. This hypothesis
assumes that the early animals, to a greater or less degree, h
origin in the same waters, and like the plants on which they were
ent spread thence to the sea and out upon the land. It is c
that there might be considerable development of the aquati
of animal life, such as the fishes,[1] mollusks,[2] crustaceans, etc.
land waters before they became denizens of the seas, and their
ance in the latter might be at some rather advanced stage
evolution and hence be seemingly sudden. As has been note
only after the ocean waters were plentifully enriched in v
matter that the stationary forms of marine life could be su
supplied with food. This enrichment, however, does not ne
imply a very great period, geologically speaking.

It is doubtful whether either of these suggestive hypothes nizes sufficiently the fact that a great evolution of ancestral forms must apparently have taken place in a common body of water, and in close association with one another, for their defensive coverings are good evidences that they had lived and battled together long enough to evolve these and all the structures, habits, activities, and dependencies that go with them.

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[1] T. C. Chamberlin, On the Habitat of the Early Vertebrates, Jour.
Vol. VIII, 1900.

[2] F. W. Sardeson, The Phylogenic Stage of the Cambrian Gastropoda
Geol., Vol. XI, No. 5, 1903.

CHAPTER VI.

THE ORDOVICIAN (LOWER SILURIAN) PERIOD.

Formations and Physical History.

That no considerable physical change took place in th of land and water in North America at the close of the Camb as usually defined is shown by the general conformity b Ordovician and Cambrian systems. Where unconformity e relatively slight. There is here no considerable "lost interv which the record of sedimentation is unknown, and the shows the relations of land and water in our continent a of the Cambrian (Fig. 95) serves also to indicate their r the opening of the Ordovician.

It has been seen that during the Cambrian period, so fa America is concerned, the sea slowly encroached on the lan the Ordovician period which followed, the climax of the tr was reached, and an epicontinental sea (Vol. I, p. 11) stood of the continent (Fig. 129). This general statement is not strued to mean that the continental area was altogether with ment during this period. There is reason to believe that and local oscillations of level, either of the land or of the both, sufficient to change conditions of sedimentation, wer many times and in many places during the period, and close, geographic changes of great importance took place.

Sedimentation During the Ordovician Perio

So long as the sea was encroaching on the land, as in brian period, the sediments deposited within the contin were predominantly clastic. Deposits of organic sedime coral, etc., and their comminuted products), together wit less land-derived detritus, were being made in the clearer wat

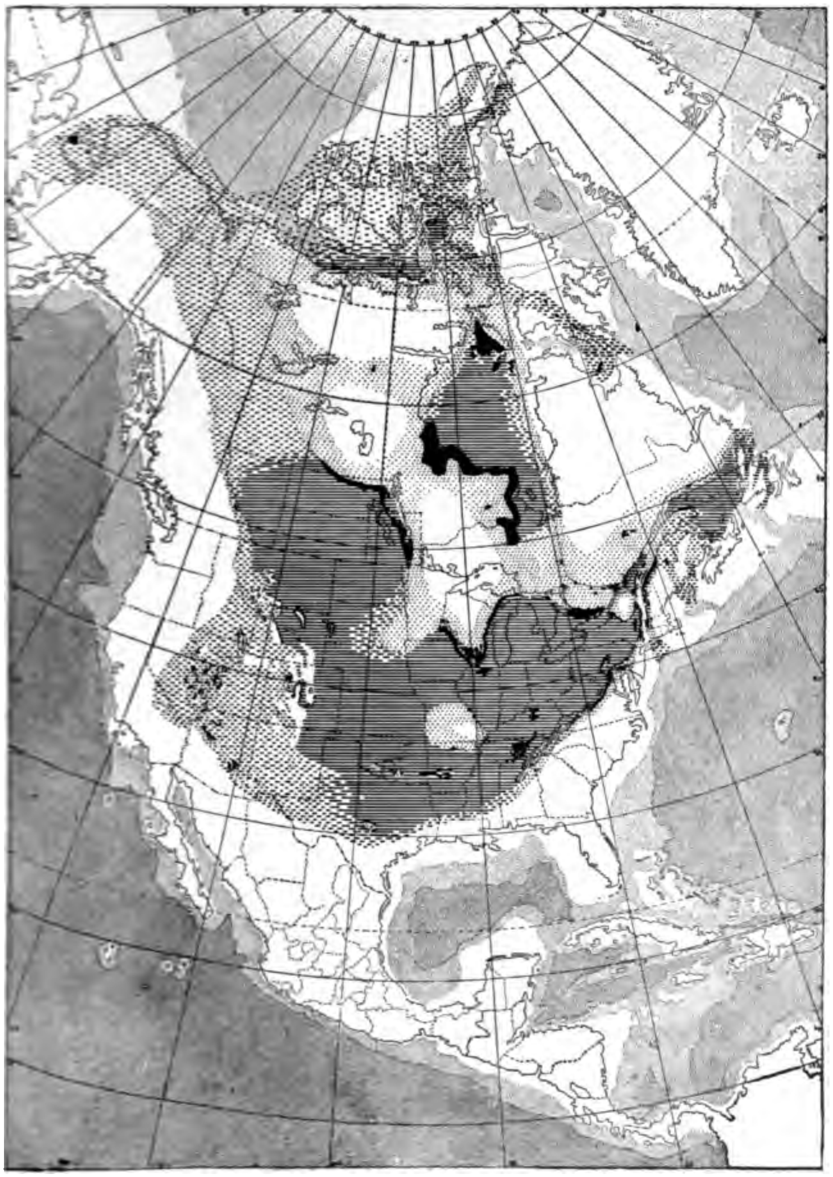

FIG. 129.—Map showing the general condition of the North American continent in Mid-Ordovician (Trenton) time. The black portions represent areas where the Middle Ordovician beds appear at the surface. These areas so nearly correspond with the areas where the Ordovician system as a whole appears at the surface that no serious error is involved if the black areas be interpreted as Ordovician The various conventions of the map are the same as in Fig. 38, p. 147.

the reach of abundant terrigenous sediments; but within of the North American continent such formations were unimportant.

The conditions of sedimentation during the Ordovician p somewhat different from those of the Cambrian period. T lands as still remained, the winds, the rains, the changes o ture and the plants and animals, if then present, operated, the rock and preparing it for removal to the sea. But the area of the land within North America was attended by in the amount of terrigenous sediment transported to the the increased (though still shallow) depth of the epicontinen tended to prevent its transportation far from shore. While t tion of terrigenous sediment was in progress near the land, ot of sedimentation were in progress farther from it, where v dust, and shells and skeletons of marine animals and pl accumulating.

Since the land areas of the Ordovician period were of va of various sorts of rock, and presumably of various heights, apparently existed for the deposition of all sorts of sedime their borders. The conditions which determined variatio sediment also influenced the rate of sedimentation. The tion was doubtless more rapid along the borders of such a as that in the eastern part of the United States, than about t islands at various points farther west, and sediments must hav more rapidly on that side of any land mass towards which part of its drainage was directed, than on the other.

The sediments deposited during the Ordovician period a ing with these general principles. Adjacent to the broa deep arm of the ocean which covered the larger part of the basin (Fig. 129) there appears to have been no source of sediments. Along the western base of the elongate tract of la lachia) in the eastern part of the United States, mud, sand, a washed down from the land, were being deposited. In g coarser materials were left nearer the land, while the finer w farther out. Alternating beds of coarse and fine sediment cate either that the adjoining land was higher at some tim others, or that the climatic conditions or the vegetal covering or that waves and currents varied in their strength. Along where the Appalachian mountain system was to appear later, limestone, the product of clear waters, is very subordinate to clastic rocks among the formations of the Ordovician system. Concerning the formations made along the eastern border of Appalachia, little is known. If the Ordovician shore was east of the present coast, the formations of the period are obviously not exposed; if it was west of the present coast, the sediments deposited within the present land area were either subsequently removed by erosion, or are concealed by later beds, or have been metamorphosed, for the most part, past recognition.

The beds of sediments forming at the same time in Newfoundland and in the northeastern parts of Canada were largely of limestone, indicating that abundant débris from the land was not brought to this region. Likewise in the area west of the Adirondacks, in the Ottawa basin, the prevailing sedimentation seems to have been organic rather than clastic, indicating that the land to the north was not furnishing abundant sediments to this region, either because it was low, or perhaps well clothed with vegetation, or because the drainage was in some other direction.

About the isolated land masses farther west, beds of sand and mud, subsequently to become sandstone and shale, were in process of accumulation; but the sources of material appropriate for such formations were not extensive, and the formations themselves are correspondingly limited. Here the conditions for the formation of limestone prevailed, for while shell-bearing and other lime-secreting animals and plants may have been no more abundant far from land than near it, their shells were probably more abundant *relative to the sediments derived from the land.* The occasional variations from limestone to shale or sandstone in this region were probably connected with oscillatory relations of land and sea, or currents. When the land was low, and the waters relatively free from terrigenous sediments, limestone appears to have been making; when the land was higher, more material was brought to the sea by the streams; and where the ocean water was shallow, this material was carried relatively far from the land whence it came.

But even during those intervals when the land was so low as not to yield abundant sediments, preparation was making for future formations of clastic rock. While in this attitude, the formations of the

land were undergoing decay, even though the products of d
not removed. Under these conditions, thick mantles of resid
accumulate, representing the excess of rock decay over t
tion. When, after such intervals of rock decay, uplift of
gives the streams transportive power, they find a large amou
integrated material ready for removal. Under such conditi
surfaces are rapidly degraded, and sediments rapidly ac
about them.

Concerning the Ordovician strata of the western portion
America much less is known, since most of the region has
studied in detail; but it is safe to assume that the same
governed by the same principles, were there in operation.
strata are known in the Black Hills of South Dakota,[1] in I
ritory,[2] Texas,[3] at various points in New Mexico, Arizona, C
Utah,[5] Nevada,[4] Wyoming,[6] Montana, Colorado,[7] and British
and are doubtless present over considerable areas where
pletely concealed.

Looked upon as a whole, the sediments of the Ordovici
were as wide-spread as the Ordovician seas themselves. To
preceding formations of rock so situated as to be subject t
contributed, and their development meant the destruction of
alent body of older rock. The old material which entere
new system was brought from the land by streams,
its shores by waves, or blown to the sea by winds; and wh
enous sediments failed, or where they were relatively uni
the shells and other secretions of animals and plants acc
giving rise to sedimentary rocks of organic origin. Even
their ultimate source in the older formations, for the mine
extracted from the sea to make the shells had been disso

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[1] Todd, Geology of South Dakota; and Jaggar, 21st Ann. Rept. U. S.
Pt. III, p. 178.

[2] Taff, Atoka folio, U. S. Geol. Surv. and Professional Paper No.

[3] Richardson, Bull. 9, Univ. of Texas Min. Surv., p. 32. The Ordov
unconformable on the Cambrian; idem., p. 27.

[4] Spurr, Bull. 208, U. S. Geol. Surv.

[5] King, Geol. Surv. of the 40th Parallel, Vol. I.

[6] Absaroka and Yellowstone folios, U. S. Geol. Surv.

[7] King, op. cit. and Anthracite-Crested Butte, Pike's Peak and Te
U. S. Geol. Surv.

[8] Dawson, Bull. Geol. Soc. Am., Vol. XII, p. 68.

older formations during the process of their decay, and brought to the sea in solution by the same streams which brought the mud in suspension.

While the rocks of the Ordovician system were as widely distributed as the Ordovician seas, their present exposures (Fig. 129) are much less extensive, for they are to be seen only where they have either never been covered by later formations, or where the beds which once overlay them have been removed by erosion. These areas, taken together, are relatively small. Elsewhere, where the Ordovician rocks exist, they are buried by later deposits, and are, for the most part, inaccessible. They are known, so far as known at all, only by inference, and by the meager data afforded by borings and excavations. But even by these imperfect means, it is known with a reasonable degree of certainty that the Ordovician system underlies much of the eastern interior of North America, though concealed by later beds. The general stratigraphic relations of the Ordovician system where the strata have not been greatly deformed are shown in Fig. 136.

It is probable that the larger part of the ocean basins was continuously submerged during the Ordovician as during earlier periods, and that in them the Ordovician strata overlie conformably those of Cambrian age. Though nothing can be known directly of the Ordovician system beneath the sea, it is important, in the conception of the system as a whole, to remember that it probably underlies most of the ocean, as well as many of the younger formations of the land, and that its exposed margin is but a trivial fraction of its total area.

Sections of the Ordovician.

New York section.—The strata of the Ordovician, like those of every other system, are divisible into series and formations, both on lithological and paleontological grounds. In North America the formations were first studied systematically in New York, and the New York section remains in some measure the standard to which others are referred. On the basis of variations in the formations themselves and in the fossils which they contain, the system in New York was early divided into five formations. Numbered in the order of their sequence, these subdivisions are as follows:

Ordovician system........	5. Hudson River formation
	4. Utica formation
	3. Trenton formation
	2. Chazy formation
	1. Calciferous formation

Most of the above names are derived from localities wh
rocks representing the several epochs are exposed. It is not
understood that these epochs were of equal duration, or that t
responding formations are equally thick or equally distinct. T
two formations have sometimes been grouped under the name
dian, and the last three under the name Trenton, though this g
has little significance.

Recently it has been proposed [1] to substitute the following cl
tion for that hitherto in use:

Champlainic [2] (Lower Silurian or Ordovician)	3. Cincinnatian (Neo-Champlainic)	Richmond beds [3] (Ohio and I Lorraine beds Utica shales
	2. Mohawkian (Meso-Champlainic)	Trenton limestone Black River limestone Lowville limestone
	1. Canadian (Paleo-Champlainic)	Chazy limestone Beekmantown limestone

With reference to this classification, it may be said that there
no adequate reason for supplanting the term Ordovician. Th
division of the system into three main series, a lower, a midd
an upper, is certainly to be commended on the basis of conve
So much of the classification is applicable universally. The
visions in the right-hand column above are based on the detaile
of recent years, and must be accepted as best expressing present
edge of the system in New York. The relations of the old a
new classifications to each other are evident on inspection.

Perhaps the following may be accepted for the present as th
satisfactory compromise:

Ordovician	Upper Ordovician (or Cincinnatian)	Richmond beds (Ohio and Indiana) Lorraine beds Utica shales
	Middle Ordovician (or Mohawkian)	Trenton limestone Black River limestone Lowville limestone
	Lower Ordovician (or Canadian)	Chazy limestone Beekmantown limestone (=Calcifer

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[1] Clark and Schuchert, Science, Vol. X, 1899, p. 876; and Am. Geol., Vo
1900, p. 118.

[2] The term Champlainic was proposed by Hall, Vanuxem, Mather, and E
in 1842, to include what is now known as Ordovician and the Potsdam.

[3] Winchell and Ulrich, Geol. of Minn., Vol. III, Pt. 2, p. ciii; and Nick
Geol., Vol. XXXII, p. 202.

The above subdivisions of the system indicate that successive epochs of longer or shorter duration gave rise to recognizable differences in sedimentation, and that these differences in sedimentation were accompanied by faunal changes, usually not profound. The general conformity between the several formations of the system, and the conformity of the lowest with the Cambrian, shows that great geographic changes did not affect the region of New York while the Ordovician strata were in process of deposition. Locally, beds corresponding to the Chazy are wanting, but even in such areas there is only a moderate unconformity between the Beekmantown formation and the Middle Ordovician series. The land surface of the Chazy epoch, where there was land, seems therefore to have been low and subject to little erosion.

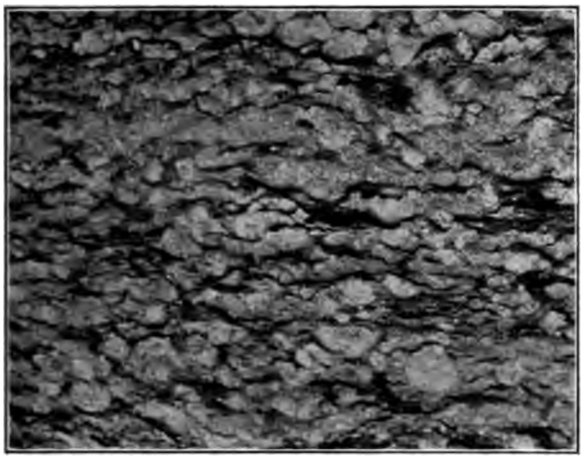

FIG. 130.—Chazy limestone. From Phelps Point, Grand Isle, Vt. Shows *Strephochetus oscellatus*.

The lowest formation in New York (the Calciferous or Beekmantown) is an impure limestone, or sometimes a calciferous sandstone. During its deposition, the general relations of land and sea remained much as in the late Cambrian. After it had attained a thickness of a few hundred feet, change of relations affected much of the Appalachian trough, converting into land considerable areas which had been submerged. After these disturbances had taken place, the only part of New York known to have remained under water is an area in the extreme northeastern part of the state, to which a bay from the Atlantic reached. In this bay the sediments of the Chazy formation were deposited.

The life of the bay, as shown by the fossils, was somewhat unlike had inhabited the same region during the preceding epoch. Both in basin, and in a long narrow channel to the east (the Levis channel, from Newfoundland to near Albany) the fauna of this epoch had mo to that of Europe than to that which lived at the same time in the basin.[1] After the Chazy limestone had attained a thickness of sever feet, the Chazy basin appears to have been drained, and at about the the sea again invaded New York, entering from the south and wes deposition of limestone (the Middle Ordovician) was resumed on t which had for a time been land. The fossils of the new formation those of the formation on which it rests. Later, the deposition o gave place to the deposition of mud (Utica shale). During this epoch,

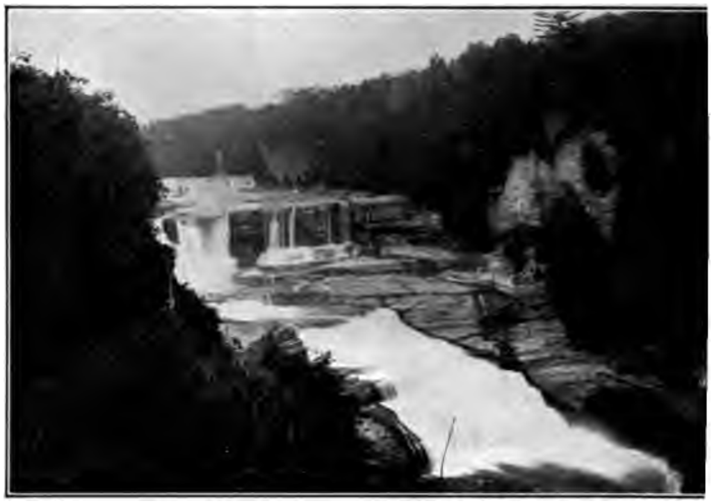

FIG. 131.—Trenton Falls, Trenton, N. Y. The locality whence the formation derived its name. (Darton, U. S. Geol. Surv.)

was again made between the Atlantic and the eastern interior sea the St. Lawrence valley,[1] as shown by the migration of animals from body of water to the latter. After the Utica formation had reach ness varying from a few feet in some places to a few hundred feet in ot buried beneath other sediments (the Hudson River or Lorraine form taining the relics of a somewhat different fauna. The successive faunas probably indicate changes in the geographic conditions of though their character and extent are not definitely known. With tion of the changes noted above, the Ordovician seems to have be region, a period of general quiet, though oscillations of relative lev land and sea doubtless took place more than once during its progre

[1] Ulrich and Schuchert, N. Y. State Museum, Bull. 52, pp. 633-

Southern Wisconsin section.—It is not to be understood that the same subdivisions hold for the Ordovician system in all regions, and even if the same number of subdivisions is made elsewhere, it does not follow that they are equivalent, severally, to those of New York.

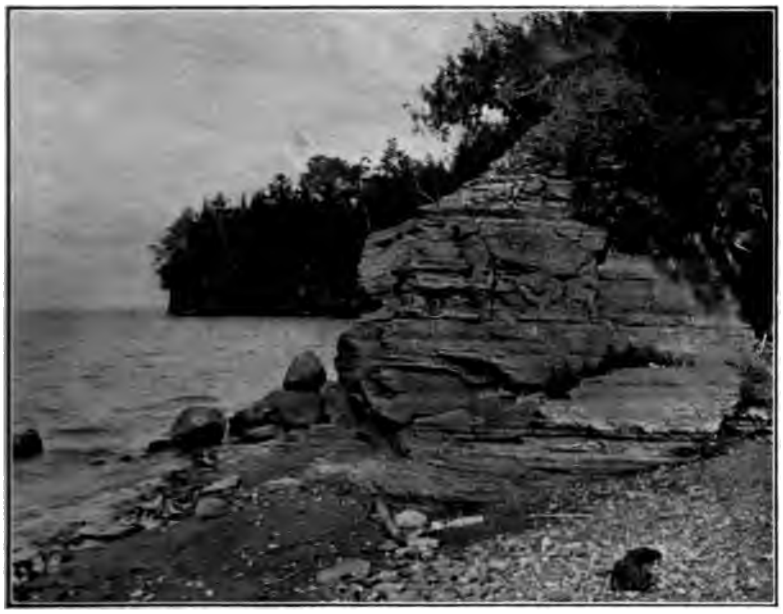

FIG. 132.—Exposure of the Utica shale. Bluff at Van Tine's, on the west shore of Grand Isle, Lake Champlain. (Perry.)

In Wisconsin, Iowa, and Minnesota, for example, the formations commonly recognized, numbered in the order of their deposition, are as follows:

Upper Ordovician	5. Hudson River (Cincinnati) shale.
Middle Ordovician	4. Galena limestone. 3. Trenton limestone.
Lower Ordovician	2. St. Peters sandstone. 1. Lower Magnesian limestone.

While there is here, as in New York according to the older classification, a fivefold division of the system, it is not certain that any formation of Wisconsin is the exact equivalent of the formation which occupies the corresponding position in the New York sect stone or dolomite beds (Knox, Chickamauga, Moccasin, etc.), t not distinctly marked off from the Cambrian below, is follo series of clastic beds (Sevier shale, Bays sandstone, etc.).[1] limestone (the Moccasin) of one area is thought to be the e of the sandstone (the Tellico) of another but a few miles av exact relations of these formations to those of the northwest been determined. If the upper part of the Knox dolomite is tl lent of the oldest Ordovician formation of the Upper Mississiı it would simply mean that when the conditions of sedimentatio in the latter region so as to stop the formation of limestone (Magnesian) and to give rise to the deposition of sand (the S they did not change correspondingly in Tennessee, where sition of limestone continued. Two formations (lithologi sidered) in one locality, may well be the equivalent of one i locality. Could the strata of Wisconsin be traced uninterrı Tennessee the relations might be determined, but since between these localities are chiefly concealed, the relations mations in the two localities must remain unknown, excep as the fossils may reveal them.

It seems not improbable that the change from calcareous sedimentation in the southern Appalachian region took pl end of the Middle Ordovician time. In the early part of vician, when similar changes occurred elsewhere, a bay open ward to the ocean is thought to have occupied the south Appalachian synclinorium, and to have been shut off from t sea. For this region a two-fold division of the system, a an upper, seems quite as appropriate as a three-fold divi subdivisions of the system are different in other parts of easter and different names are applied to them.

In central Tennessee, the Ordovician is made up chiefl stone which is sometimes phosphatic. There are here seve formities in the system, indicating that shallow water and ditions alternated.[2]

The following sections in the Appalachian province, g Ordovician and Silurian formations, supplement those of the

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[1] The subdivisions here mentioned are those of the Maynardville, U. S. Geol. Surv.

[2] Hayes and Ulrich, Columbia, Tenn., folio, U. S. Geol. Surv.

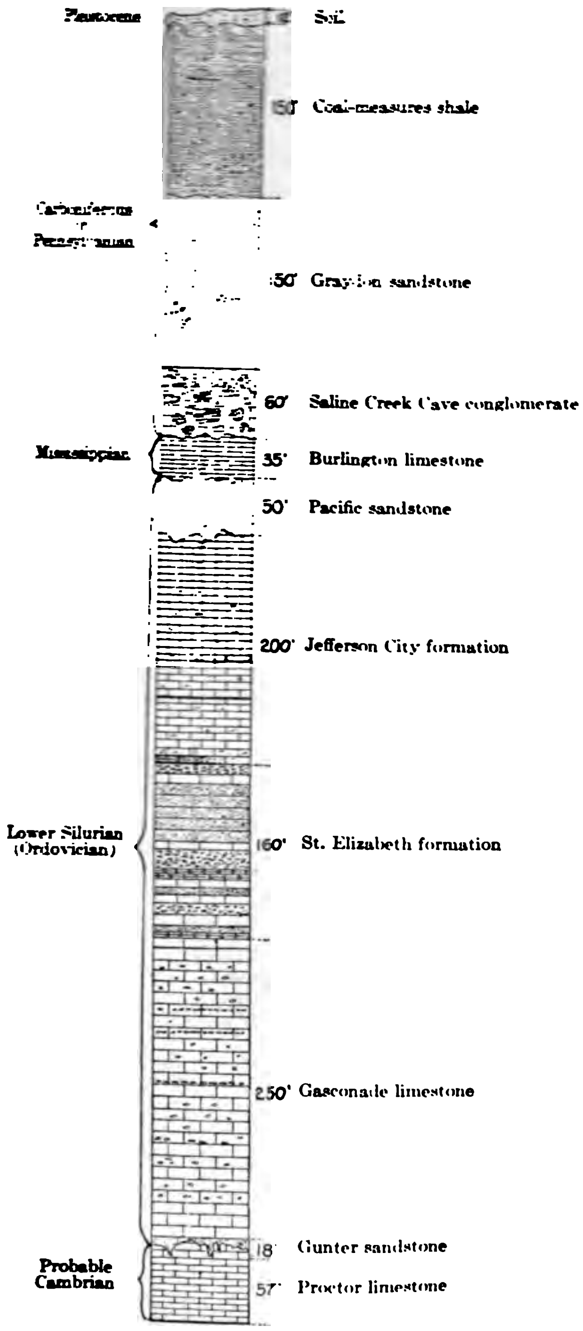

FIG. 135.—A generalized section for Miller County, Missouri. Unconformities are shown between the Cambrian and Ordovician, between the Ordovician and Mississippian, and between the Mississippian and Pennsylvanian, as well as one in the Ordovician and one in the Pennsylvanian. (Buckley.)

SECTION IN NEW JERSEY.[1]

	Names of Formation.	Thickness in Feet.	Characteristics.
Silurian.	Manlius limestone....	35	Thin-bedded, knotty, dark-colore
	Rondout limestone...	39	Earthy and calcareous shales and
	Decker Ferry formation (Cobleskill limestone)........	52	Sandstones with calcareous band stones with shaly bands.
	Bossardville limestone.	100	Fine-grained, compact, bluish-gra
	Poxino Island shale...	?	Buff or greenish, calcareous; bedded; layers thin.
	Medina sandstone.....	2305	Soft red, somewhat shaly sandsto
	Shawangunk conglomerate.........	1500–1600	Coarse quartz conglomerate; p ally white or yellowish, with g matrix
Ordovician.	Probable unconformity		
	Hudson River slates..	1165	Shales, slates, and some sandstone
	Trenton limestone....	135–150	Limestone, often conglomeratic a shaly above.
	Unconformity.		
	Kittatinny limestone (mainly Cambrian).	2700–3000	Dolomitic; at one locality the formation contains Ordovician f

SECTION IN WESTERN MARYLAND.[2]

	Names of Formations.	Thickness in Feet.	Characteristics.
Silurian.	Salina..............	....	Sandstones, shales, and limestones
		700	Sandstones predominate in lowe stones in upper portions.
	Niagara.............	300	Limestones with shale partings; stone beds near the top; shales p over limestone at the top.
	Clinton..............	550–600	Thin reddish and greenish-yellow sandstone beds, and in the uppe thin beds of limestone.
	Tuscarora...........	250–300	Snow-white to light-gray quartzite cross-bedded.
	Juniata.............	550	Dull-red sandstones and shales, i irregularly; shales predominate.

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[1] Weller, Geol. Surv. of New Jersey, Report on Paleontology Vol. III 15–80.

[2] Prosser, Jour. of Geol., Vol. IX, pp. 410–415.

The above section is for Allegany County. In Washington County, lower formations are exposed as follows:[1]

Ordovician	Martinsburg.........	700–1000	Black and gray calcareous and argillaceous shales, fine-grained and uniform.
	Shenandoah......... (The lowest part of this formation is Cambrian.)	2500	Blue and gray limestones and dolomites, with some slates and argillaceous shales.

Strata much folded.

SECTION IN EASTERN KENTUCKY.[2]

	Names of Formations.	Thickness in Feet.	Characteristics.
Silurian	(The upper part of this formation is Devonian) Panola formation.....	1–70	Brown siliceous limestone at the base; light blue clay-shale and coarse yellow sandstone; brown limestone, frequently cherty.
	Unconformity.		
Ordovician	Richmond formation..	300	Blue calcareous shale, with thin beds of limestone.
	Garrard sandstone....	70–100	Brown, calcareous.
	Winchester limestone.	200–230	Thin-bedded, blue, crystalline, with bands of calcareous shale.
	Flanagan chert.......	0–40	Thin-bedded, gray limestone and calcareous shale; nodules and bands of chert.
	Lexington limestone..	140–160	Thin-bedded, gray; nodules of chert at base.
	Highbridge limestone.	190+	White limestone grading downward into gray limestone and calcareous shale.

Strata nearly horizontal.

Sections in the interior.—In the interior the sections are likewise variable.[3] The sections of the Ordovician, in the general sections given in the Appendix, give some idea of the range of the system in this region. To these may be added the following:

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[1] Clark, Maryland Geol. Surv., Vol. I, pp. 179, 180.

[2] Campbell, Richmond (Ky.) folio, U. S. Geol. Surv. All the formations of this section are classed as Silurian in the folios.

[3] The following folios give detailed sections of the exposed Ordovician between the Appalachians and the Rockies: London and Richmond, Ky.; Columbia, McMinnville, Pikeville, Sewanee, and Standing Stone, Tenn.; Atoka, I. T. See also state reports of New York, Ohio, Indiana, Michigan, Illinois, Wisconsin, Minnesota, Iowa, Missouri, Kentucky, Tennessee, and Arkansas. For areas north of the United States, see the geological reports of Canada.

SECTION IN SOUTHEASTERN MINNESOTA.[1]

	Names of Formations.	Thickness in Feet.	Characteristics.
	Devonian		
Silurian.	Unconformity.		
	Niagara(?) limestone..	100–150	Light-colored crystalline limest porous.
	Unconformity.		
Ordovician.	Maquoketa shales.... (=Hudson River)	75–100	Shales; some sand, finely bedded.
	Galena limestone.....	75–100	Bluish or grayish, evenly bedde from compact to vesicular; arenaceous and often dolomitic.
	Trenton limestone....	160	Light blue or gray; non-dolomitic.
Cambrian.	St. Peter's sandstone..	122	White and friable.
	Shakopee limestone...	75	Irregularly bedded, cherty; concret brecciated layers; heavy-bedded shaly layers.
	New Richmond sandstone............	25–40	Coarse quartzose sandstone, somet herent; sometimes cemented.
	Lower Magnesian limestone.........	200	Yellowish, dirty-appearing limesto bedded below; thin-bedded abo arenaceous.
	St. Croix (=Potsdam sandstone)		

SECTION IN CENTRAL TEXAS.[2]

	Names of Formations.	Thickness in Feet.	Characteristics.
Silurian and Ordovician	Unconformity.		
	San Saba........	315±	Dolomites and chert.
	Leon...........	440+	Sandy shaly dolomite; siliceous limestone; brown dolomite marble.

Strata nearly horizontal. The equivalent of the Niagara is apparen Thicknesses given are incomplete.

In Arkansas the system, though largely of limestone, thick beds of novaculite,[3] a fine pure siliceous sandstone, fro whetstones are made. In the southwest, the Ordovician and seem not to be well differentiated. This is indicated by the sections of Texas [1] and Indian Territory.[2]

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[1] Winchell, Geol. and Nat. Hist. Surv. of Minn., Vol. I, 1872–82, p. 280, Revised to agree with nomenclature of frontispiece of Vol. VI, atlas 1900– and Nat. Hist. Surv. of Minn. The Shakopee, New Richmond, and Lower formations of Minnesota correspond to the Oneota of Iowa, and to the L nesian of Wisconsin.

[2] Dumble, Geol. Surv. of Texas, 1st Ann. Rept. Pl. III.

[3] Griswold, Ark. Geol. Surv. Ann. Rept. 1890, Vol. III.

General conditions in the eastern part of the continent.—It is worthy of note that in mid-Ordovician time, limestone was forming over a very wide area in the eastern part of North America, namely, from New England on the east to Georgian Bay on the northwest, Indian Territory and Texas on the southwest, and Alabama on the south. Limestone appears to have been forming in the Great Basin region of the west at the same time. At no previous epoch in geological history, so far as now known, was there anything like so wide-spread deposition of limestone within the limits of North America. This is to be accounted for by the fact that the sea occupied a large part of the continent, that such lands as existed were low, and that drainage from them brought little sediment to the sea. Meanwhile the forms of life which secrete lime carbonate were depositing their shells widely over the bottom of the interior epicontinental sea.

It is perhaps equally worthy of note that in the latter part of this period mud (now shale) was deposited over an almost equally extensive area extending from New York southwest to Alabama and northwest to Manitoba and beyond.

The inauguration of the epoch of clastic sedimentation may have been brought about by movements which increased the capacity of the ocean basins, thereby drawing off the waters, attended by gentle warpings which resulted, among other changes, in the uplift of an area about Cincinnati [3] (the Cincinnati arch) and the closing of the southern outlet of the bay which occupied the south end of the Appalachian synclinorium. It appears to have been about the same time (Utica epoch) that subsidence to the northeast reëstablished connection between the Atlantic and the interior sea by way of the St. Lawrence valley. It seems not unreasonable that these geographic changes should have been attended by an increase in clastic sedimentation. The wide-spread late Ordovician shale formation may mean either that the land areas were so far elevated as to allow the streams to carry a larger body of sediment to the sea, or that condition the transportation of the mud farther from the shores than The fineness of the sediment would seem to indicate that th were rather sluggish, though locally the sediments were coar ciated with the Upper Ordovician shales, there are considera of limestone in some places, and of sandstone in others.

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[1] Geol. Surv. of Texas, Second Ann. Rept., p. 565.

[2] Taff, Atoka (I. T.) folio, U. S. Geol. Surv.

[3] Ulrich and Schuchert, op. cit. p. 645. The time of the origin of the Cincinnati arch has never been fixed with certainty. Hayes and Ulrich place its inception still earlier in the Ordovician. See Columbia (Tenn.) folio, U. S. Geol. Surv. The region was probably subject to disturbances at various times.

It is perhaps worthy of note that all the Ordovician f of the interior and the east, unless it be the oldest, bear wit selves distinct evidence of shallow water origin, and even the formation contains no evidence that it was laid down in de Its paucity of fossils has led to the conjecture that its mat have been largely precipitated from solution.

Western sections.—In the Great Plains, the Ordovicia appears at the surface but rarely, though it probably und younger formations. West of the Great Plains, the Ordov tions, so far as now known, are simpler than in the interior o In some places the whole system seems to be represented l of a single formation of limestone. Thus in Nevada[1] a pa Pogonip formation seems to be the only representative of tl Limestone was probably in process of formation in other pa Great Basin and in western Colorado[2] at the same time Rockies sand was the principal deposit in some places[3] and in others.[4] The sections of the Ordovician in the Appendix give some conception of its range in the west.[5]

Igneous rocks.—Igneous rocks of Ordovician age attain lit tance in North America. Their general absence is in harmony general quiet which characterized the period. Igneous rocks extent, which may date from the close of the Ordovician, at a few places in New York (notably Cortland County).

GENERAL CONDITIONS AND RELATIONS OF THE ORDOVICIAN

Position of beds.—It has already been indicated that t vician rocks are in general conformable on the Cambrian,

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[1] King, Geology of the 40th Parallel, Vol. I. For notes on the formation south of the 40th Parallel, see Spurr, Bull. 208, U. S. Geol. Surv.

[2] Anthracite-Crested Butte and Ten Mile (Colo.) folios, U. S. Geol. S

[3] Pike's Peak (Colo.) folio, U. S. Geol. Surv.

[4] Absaroka and Yellowstone National Park (Wyo.) folios, U. S. Geol.

[5] In addition to reports and folios already mentioned, the Ordovician system is shown on the Lassens Peak (Cal.) folio, U. S. Geol. Surv.

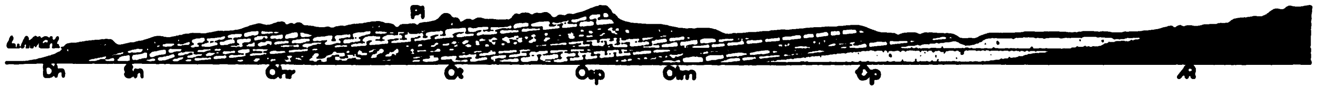

FIG. 136.—Section of the formations in southern Wisconsin, showing the position of the beds and the relations of the several systems to one another. The section extends from the Archean area, in the north-central part of the state, to Lake Michigan, in the vicinity of Milwaukee. *Æ*, Archean; *Ꞓp*, Potsdam sandstone (Cambrian); *Olm*, Lower Magnesian limestone; *Osp*, St. Peter's sandstone; *Ot*, Trenton and Galena limestone; *Ohr*, Hudson River shales. The last four formations are Ordovician. *Sn*, Niagara limestone (Silurian); *Dh*, Hamilton limestone (Devonian), and *Pl*, glacial drift (Pleistocene). The structure shown by the section is the structure characteristic of the Ordovician in much of the interior. Length of section, about 135 miles. (Chamberlin, Wis. Geol. Surv.)

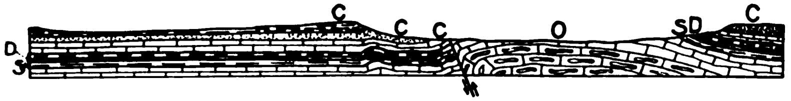

FIG. 137.—Section showing the relation of the Ordovician to Silurian, Devonian, and Carboniferous beds in eastern Tennessee. The removal of the top of a gentle fold by erosion has exposed the Ordovician. A fault on one side has concealed the Silurian and Devonian so that the Carboniferous appears next the Ordovician. *O* = Ordovician; *S* = Silurian; *D* = Devonian; *C* = Carboniferous. Length of section, about 7½ miles. The Ordovician and Silurian are combined in the original. (Hayes, Pikeville (Tenn.) folio, U. S. Geol. Surv.)

the principles which have heretofore been set forth, it is c
they must rest unconformably on formations older than the C
where such formations constitute their substratum.

As originally deposited, the Ordovician beds probabl
away from such lands as then existed. Thus on the soutl
the land of northern Wisconsin (Fig. 136), the Ordovician s
must have dipped slightly to the south, and on the east and w
to the east and west respectively. The same relations m
held originally about the Adirondacks, and about every ot
area from the borders of which the sea-bottom declined. O
areas in the interior,[1] this original and simple plan of str
has been but little modified.

In other regions, deformation of the strata subsequent
deposition has completely changed their position. Thus in t
lachian mountains, where the sediments were derived princip
the land to the east, and where the beds doubtless had a s
to the west at the time of their deposition, they now dip i
directions and at various angles, some of them being nearly
Faulting has complicated their relations still further (Figs.
and 139).[2] The same is true of the formations of the syst
the eastern border of New York and the western borders of t
adjacent on the east.[3] The strata are in similar positions
parts of Arkansas[4] (Fig. 140), Indian Territory,[5] Oklahoma
various mountain ranges of the Cordilleran system.[6] Even w
beds are not folded, they are sometimes affected by faulting.

Present condition of the formations.—Aside from the ch
position which the Ordovician beds have suffered, as noted a
sediments as originally deposited have undergone more or le
tion. In some cases the change has been slight, and in othe
Many of the beds of sand and mud have been simply compa
cemented; indeed the greater part of the Ordovician sands

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[1] See footnote, p. 319.

[2] For references, see p. 315.

[3] Walcott, The Taconic system of Emmons, etc., Am. Jour. Sci., Vo
1888. Also Merrill, New York City folio, U. S. Geol. Surv.

[4] Geological Reports of Arkansas, especially reports of 1890. Vols. I
and IV (Hopkins).

[5] See references on p. 319.

[6] See references on p. 318.

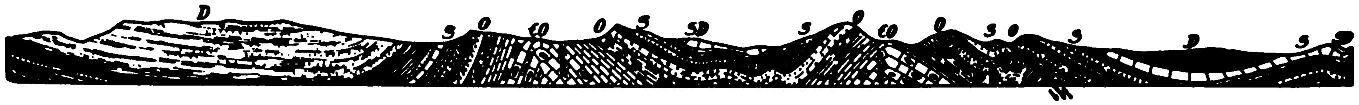

FIG. 138.—Section showing the relations of Ordovician and other beds at a point in West Virginia. *€O*=Cambro-Ordovician; *O*=Ordovician; *S*=Silurian; *SD*=Siluro-Devonian; *D*=Devonian. Length of section, 18 miles. (Darton, Monterey (W. Va.) folio, U. S. Geol. Surv.)

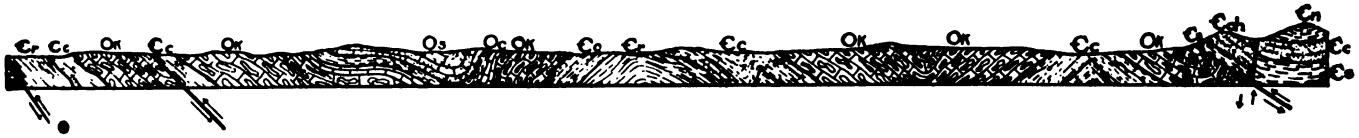

FIG. 139.—Section showing the position and relations of Ordovician, *O*, and other beds in the mountains of eastern Tennessee. *€s*, Sandsuck shale; *€ch*, Cochran conglomerate; *€n*, Nichols shale; *€r*, Rome formation, and *€c*, Connesauga shale, are Cambrian formations. *Ok*, Knox dolomite, the lower part of which is Cambrian. *Oc*, Chickamauga limestone, and *Os*, Sevier shale, are Ordovician. (Hayes, Cleveland (Tenn.) folio, U. S. Geol. Surv.)

in the condition of sandstone, and the greater part of the mu condition of shale, and most of the limestone is still essentia metamorphic. This is true over the great interior, but where action has been great, and where the original position of th has been greatly changed, the changes in the rock have also bee Thus in the Taconic mountains of New York, Vermont, and M setts, the limestone is mainly in the condition of marble, tl stone and quartzite have been largely changed to quartz scl

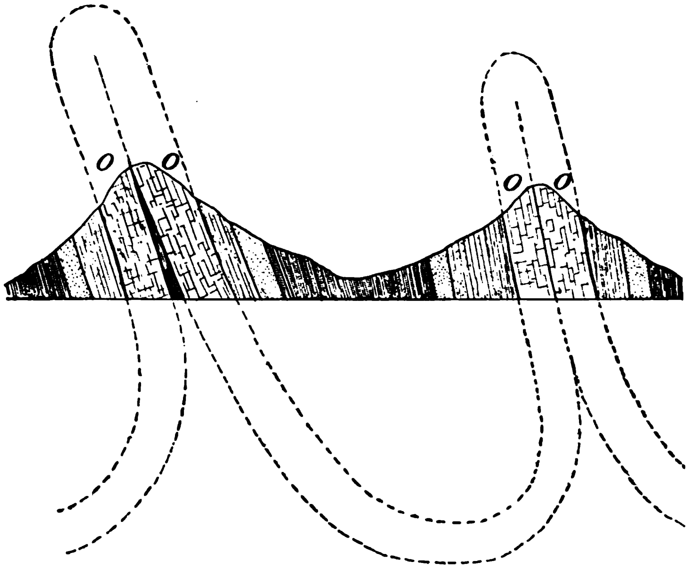

FIG. 140.—Section showing the position and relations of the Ordovician be mountains of Arkansas. Length of section, about 1½ miles. (Penn Geol. Surv.)

the shales to slate and schist. The same is true in some oth of New England, and at various points in the Appalachian of New York.

Exposure of the Ordovician rocks.—Theoretically, the Or rocks, like those of other systems, may be found at the surfac they were never buried, and where any cover they once p has been worn away. The areas where they have never been fall into two categories: First, the elevation of a land-mass which Ordovician sediments had gathered would have given t

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[1] See New York City (N. Y.), Holyoke (Mass.-Conn.), and Hawley (Mas U. S. Geol. Surv.

composed of pre-Ordovician formations a border covered by Ordovician sediments, which might never have been submerged and buried (see Fig. 141); and second, any part of the Ordovician sea-bottom distant from preëxistent land might have been raised to the estate of land at the close of the Ordovician period. If never covered by younger beds, it would belong in the category here specified (Fig. 142).

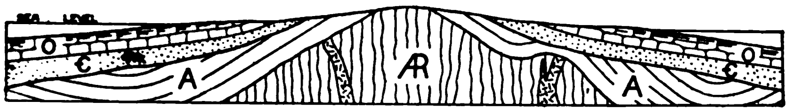

FIG. 141.—Diagram illustrating the exposure of Ordovician beds about a center of older rock. The diagram illustrates exposure of the Ordovician beds by emergence after the Ordovician period.

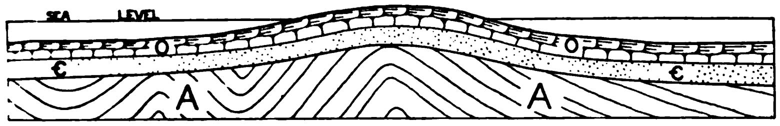

FIG. 142.—Diagram illustrating the exposure of Ordovician beds in a region where older formations do not appear at the surface. The exposure results from emergence.

The situations where the exposed Ordovician strata were once covered, but subsequently laid bare by the removal of the overlying beds, likewise fall into two categories corresponding in some sense to those just mentioned. About the land areas of the Ordovician period, the water was presumably shallow, and here a given amount of lowering of the sea-surface relative to land would be more likely than elsewhere to bring the beds covering the Ordovician into such a position as to permit of their removal. This is illustrated by Fig. 143,

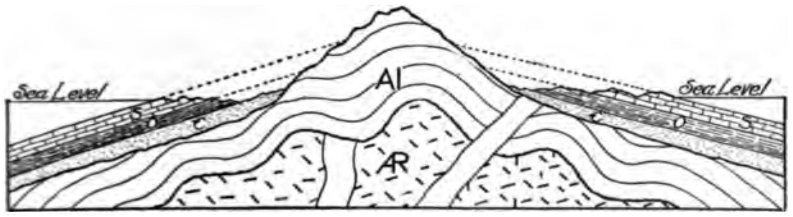

FIG. 143.—Diagram illustrating the exposure of Ordovician beds in an area where they were once concealed by younger beds, *S*, in a region where the younger beds are grouped about a center of older rock.

which represents the Silurian strata, S, as once covering th vician, O; but the removal of the former has exposed the latter. if any part of the sea-bottom not immediately associated witl existing land area were lifted above its surroundings, not at t of the Ordovician, but at some later time, the uppermost strat be in a position favorable for removal. With their removal, th vician beds beneath would be discovered (see Fig. 144). In tl illustrated by Figs. 141 and 143, the Ordovician outcrops would around or against the outcrops of older formations; in the case

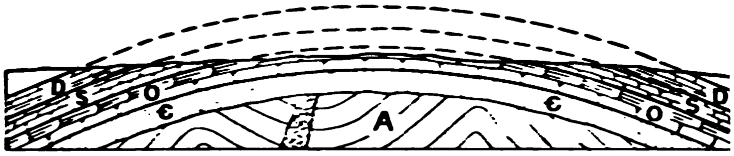

FIG. 144.—Diagram illustrating the exposure of Ordovician beds where t been discovered by erosion in a region where older formations do not the surface.

sented by Figs. 142 and 144, the Ordovician system would itsel center about which younger beds outcrop.

The map (Fig. 129) shows the principal areas where the Orc strata appear at the surface, and the relations of their outc pre-Ordovician lands (compare Figs. 38 and 95). From this m seen that outcrops of Ordovician are found along the western of Appalachia; in Wisconsin, South Dakota, Missouri, Texas, and States farther west, and also at many points north of the States. In most of these situations the outcrops of the Orc are adjacent to exposures of Cambrian or pre-Cambrian forn Where the outcrops of the Ordovician strata are next a p brian formation, rather than next the Cambrian, it means t margin of the Ordovician sea extended landward farther t Cambrian for that locality, and the deposits of the later period over and buried those of the earlier. In the vicinity of Cin in Ohio, and adjacent States, the Ordovician strata appear surface in an area where older formations are not seen. T tions are shown by Fig. 145.

If the attempt be made to refer the individual outcrops Ordovician strata to one of the categories already mentione culty is at once encountered, for it is not always possible to s

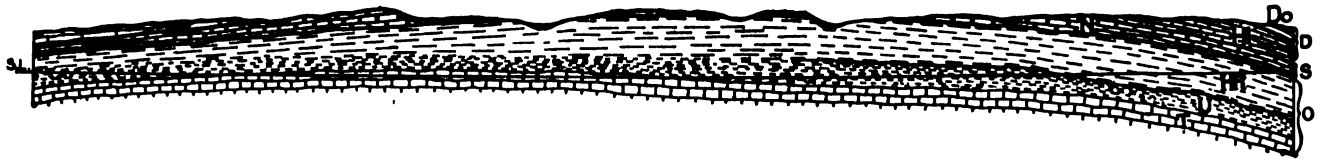

FIG. 145.—Section across the Cincinnati arch illustrating the principles shown in the preceding figure. *O*, Ordovician; *S*, Silurian; *D*, Devonian. Of the Ordovician beds, *T* = Trenton; *U* = Utica; *HR* = Hudson River. Of the Silurian beds, *N* represents Niagara. Of the Devonian beds, *Hl* = Helderberg, and *Do* = Onondaga (Corniferous). *SL* = Sea-level. Length of section, about 160 miles. (Eighth Ann. Rept., U. S. Geol. Surv.)

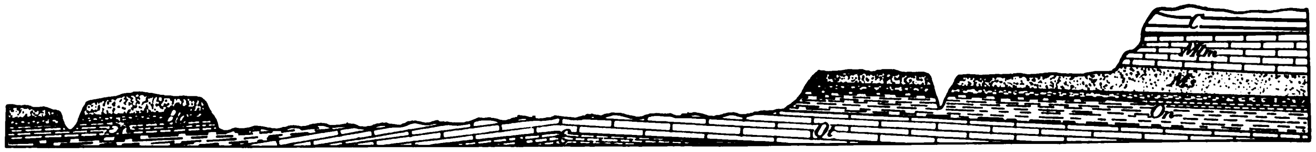

FIG. 146.—Section through the central valley of Tennessee, from Harpeth River to the top of the Cumberland plateau. Illustrates the exposure of Ordovician beds as the result of removal of overlying strata. *Є*, = Cambrian; *Ot* = Trenton limestone, and *On* = Nashville shale (Ordovician); *Sn* = Niagara limestone (Silurian); *Db* = Berea shale (Devonian); *Ms* = sandstone, and *Mlm* = Mountain limestone (Mississippian or Lower Carboniferous); *C* = Coal Measures. Length of section, about 120 miles. (Safford, Geol. of Tennessee.)

far their exposure is due to the subsequent removal of beds once overlay them. It is barely possible that in the Taconic of western New England and eastern New York, Ordovician b exposed which were never covered, except by glacial drift. portions of the exposed Ordovician in New York, Wisconsin, an States may possibly never have been buried beneath marine (of later age, though this can hardly be affirmed. It was f thought that the Ordovician beds of southwestern Ohio and a parts of Indiana and Kentucky were arched up at the close Ordovician to such an extent as to give rise to an island wh never afterward covered by the sea; but it now appears that t emergence of the "arch" occurred at a later time. The e: exposure of the Ordovician formations in this region was t probably brought about by the removal of the younger bed once overlay them (Fig. 145). The same is true of the Ordovic crops in central Tennessee (Fig. 146). In the Appalachian the exposures of the Ordovician beds are almost wholly due removal of the strata which once overlay them. The outcro] the Ouachita uplift in Arkansas, and most of those farther we: ably fall into the same category.

The Ordovician formations are wanting in some region: their presence might have been expected. Thus in the Bla of South Dakota, where, it will be remembered, there is an Proterozoic rock surrounded by a border of Cambrian, Or strata are known to be exposed at but few points. Thec there might have been a belt of Ordovician rocks surroun(Cambrian, just as the Cambrian surrounds the core of old The Ordovician system as well as the Upper Cambrian proba covered the Black Hills area. Where the system is not expos(the Cambrian, the Ordovician strata were probably removed b during some post-Ordovician period when the region was ab level. When the region was again submerged, new deposi ably covered all the Ordovician strata which had escaped de: (Fig. 147). These later beds have been removed so as to the Ordovician at but few points.

Thickness.—From what has been said it is easy to infer thickness of the Ordovician system varies greatly (see p. : Appalachian mountains it is to be measured by thousand while in the interior it is to be measured by hundreds instead (see sections pp. 318–320). In Wisconsin and Iowa, where the system seems to be full, that is, where sedimentation seems to have been continuous from the beginning of the period to its end, the aggregate thickness is somewhat less than 1000 feet.

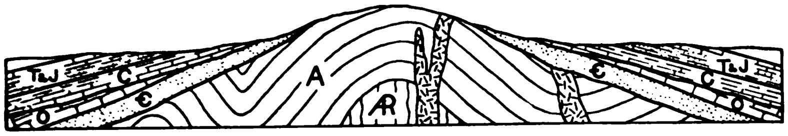

Fig. 147.—Diagram illustrating one cause of the failure of Ordovician beds to appear about a center of older rock.

Width and position of outcrops.—The relation between the thickness of a rock system and the width of the belt where it appears at the surface has already been set forth in connection with the Cambrian. The same principles are applicable here. In the interior, where the system is relatively thin, it sometimes appears at the surface in relatively wide belts or areas (Fig. 129), while in the eastern mountains, where it is thick, it appears at the surface in a succession of narrow and parallel belts.

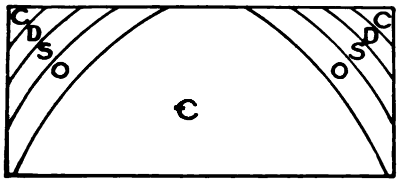

Fig. 148.

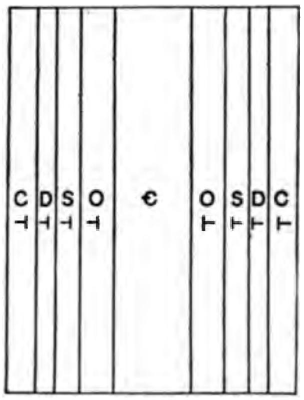

Fig. 149.

Fig. 148.—Diagram illustrating the double outcrop which the Ordovician, *O*, should show in a truncated anticline where erosion has cut down to older formations. The two outcrops should appear on opposite sides of the axis of the anticline.

Fig. 149.—Ground plan illustrating the structure shown in the last figure. The Cambrian system, *Є*, is flanked on either side by the Ordovician system, *O*, and this in turn by the Silurian, *S*, Devonian, *D*, and Carboniferous, *C*. The figure also shows the direction of the dip of the beds.

If erosion has cut off a fold down to the proper level, there be, on either limb of the anticline involving the Ordovician a belt where that system appears at the surface (Figs. 148 and but faults have in some cases had the effect of concealing th which might otherwise have come to the surface on one or bot of a truncated fold. Thus the outcrops shown in Fig. 150 would

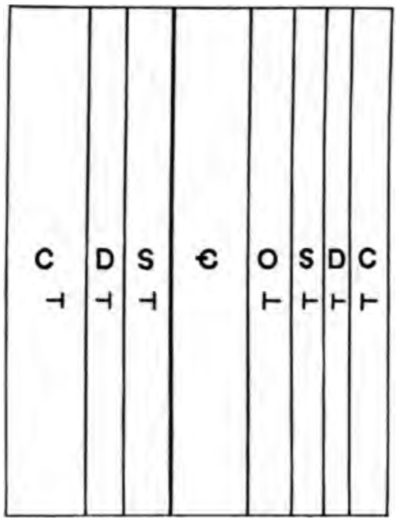

Fig. 150.

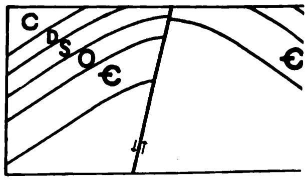

Fig. 151.

Fig. 150.—Ground-plan diagram, illustrating the failure of one system of to appear on one side of the anticline.

Fig. 151.—Cross-section showing the structure illustrated by the precedi On one side of the axis of the anticline, *Ꞓ*, *O*, *S*, *D*, and *C* appear in succe the other side, *O* does not appear.

from the faulting shown in Fig. 151. Faulting may likewise a outcrop in regions where the strata are not deformed, but is less common in such regions. The principle involved is ill by Fig. 152.

Close of the Ordovician Period.

The close of the Ordovician period was marked by ge changes of more importance than those which took place at i ning or during its progress. These changes were the result of ative movements whose cause is not fully demonstrated, b may perhaps have been due to the shrinking of the earth, i the sinking of the ocean bottoms and the draining off of the epicontinental waters to a large extent, attended by some slight deformation of the general surface of the continents and some notable flexure of special tracts. The withdrawal of the waters appears to have converted extensive stretches of Ordovician epicontinental sea-bottom into land. The land area of the Lake Superior region (Fig. 129) was greatly enlarged. From it land probably extended, via Missouri,[1] as far south as Texas, and perhaps beyond. It may have extended as far west as the Rocky mountains, and east to the Cincinnati arch. If this be true, a great expanse of land, the surface of which consisted of Ordovician strata, came into existence at this time in the very heart of the continent. The elevation of this land must have been slight, for it seems to have suffered little erosion before most of it was again submerged and covered by sediments of lesser age. It is indeed the wide-spread absence of the lower part of the Silurian system (the Oswegan series, p. 370), rather than pronounced stratigraphic unconformity between the Ordovician and the Silurian of the interior, which indicates the extensive emergence of land referred to. There is, however, an unconformity between the Ordovician and Silurian systems, in some places, as in Iowa,[2] Arkansas,[3] and Tennessee,[4] and the Devonian or later beds sometimes rest on the Ordovician, with no Silurian between. Throughout much of the western part of the continent also, the land seems to have emerged at about this time, for the Silurian system is wanting in many regions where the Ordovician is present.[5]

The folding movements were less wide-spread. The most considerable was in western New England and eastern New York, in the region of the Taconic mountains. Here both the Cambrian and Ordovician systems were thick, and at this time they were folded and lifted above the seas beneath which they had accumulated. Under the influence of the intense dynamic action involved in the folding, the rocks were

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[1] The pre-Cambrian area of Missouri is often referred to as an island at this time. It has been urged, however, that the Cambrian, Ordovician, Devonian, and Carboniferous beds once overlay it. See Keyes, Science, Vol. VII, p. 388, 1898, and Bull. Geol. Soc. Am., Vol. XIII, pp. 268–292.

[2] See Silurian, pp. 371–378.

[3] Williams, Am. Jour. Sci., Vol. 48, 1894, p. 325.

[4] Pp. 371–378.

[5] See sections of Appendix, [illegible]I.

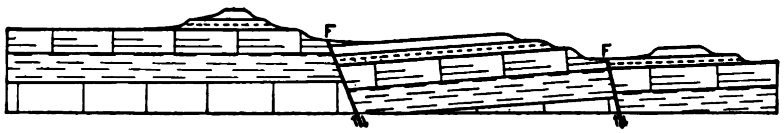

FIG. 152.—Diagram illustrating the effect of faulting, where there is no folding, on outcrops. (Hayes, Bull. 4, Geol. Surv. of Alabama.)

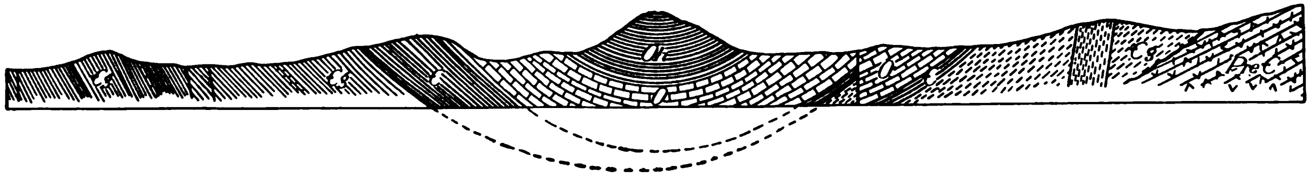

FIG. 153.—Diagram showing the structure of Ordovician and associated formations in the Taconic mountains. Pre-€, Pre-Cambrian formations; €g, slates with interbedded limestone and sandstones of the Georgian (Lower Cambrian) terrane; €, Cambrian hydro-micaceous (Potsdam) shales; O, Trenton, Chazy, and other limestones of Ordovician age; Oh, Hudson (hydro-micaceous) shales. (Walcott.)

metamorphosed, and the eroded remnants of the folds often show a complicated structure (Fig. 153). The orogenic disturbance may have extended south of New England, but its limit in this direction is undetermined.

About the borders of the mountain region, the Upper Ordovician shale is overlain unconformably by rocks of Silurian age, showing that the period of upturning and metamorphism followed the deposition of the youngest of the Ordovician formations, and preceded the deposition of the oldest formation which overlies the metamorphosed rocks unconformably. Thus the date of the upturning is, within limits, determined. The Silurian strata which overlie the Upper Ordovician do not belong to the first epoch of the period, so that in this region, there is an interval unrepresented by sedimentary formations.

The formations involved in the Taconic mountains were formerly known as the Taconic system. Their metamorphic character and complex structure long prevented their proper correlation. Within recent years it has been shown that the series includes the systems mentioned above.[1] It is not to be inferred that all the mountain-making movements which have affected western New England occurred at this time. Later movements, involving younger strata, affected this region, as will be noted in succeeding pages.

Between folding and the more gentle movements there are all degrees of gradation, and there were areas where only incipient folding or bowing of the strata took place. The "Cincinnati arch" and the "Nashville (or central Tennessee) dome" farther south have already been referred to. The deformation here was not great, but it appears to have been prolonged, and to have begun perhaps as early as the mid-Ordovician period. From this time on, the region seems to have been near sea-level, being now submerged and now land.[2]

Recently attention has been directed to another similar arch which may have come into existence at about the same time. This is in Arkansas,[3] Indian Territory, and Oklahoma, corresponding in position with the mountain system commonly known as the Ouachita uplift, of which it was perhaps the beginning. It has not been demoı that the strata of this region were deformed at this time, and were, the extent of the deformation has not been determine strata of the region were notably folded at a much later ti

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[1] Walcott, Am. Jour. Sci., Vol. 35, 1888. This paper gives bibliography (p. 30).

[2] Hayes and Ulrich, Columbia (Tenn.) folio, U. S. Geol. Surv.; also Foerste, Geol. Soc. of Am., Vol. XI, p. 604, and Vol. XIII, p. 531, Science, New Ser. Vol. X, p. 488, and 24th Ann. Rept., Dept. of Geol. and Nat. Hist. Resources of Indiana, 1899.

[3] Branner, Am. Jour. Sci., Vol. IV, 1897, p. 357. This very suggestive article has bearings on many questions besides the Ouachita uplift.

In New Brunswick and Nova Scotia there is unconformity the Ordovician strata and those which overlie them, indic emergence after the deposition of the Ordovician formation subsequent submergence before the deposition of the next strata of the region.

During the Ordovician period, as during part of the Camb eastern interior sea seems to have been connected with the A the latitude of northern New England and the Gulf of St. I During the disturbances which closed this period, this c seems to have been closed.

In the preceding paragraphs, the crustal movements re have been mentioned as occurring at the close of the Ordov would perhaps be more accurate to say that their beginning beginning of the transition from the Ordovician period to th The duration of the interval of transition was probably long.

The separation of the Cambrian system from the Ord much less marked than the separation of the latter from th which follows. For this reason it has been proposed to Cambrian and the Ordovician periods together under the nar *ozoic*, while the other periods of the Paleozoic are classe *paleozoic*.[1]

ECONOMIC PRODUCTS.

The formations of the Ordovician, especially those of t stage, constitute one of the most productive horizons of oil an Ohio [2] and eastern Indiana oil- and gas-wells have their prin in this formation. Both the oil and the gas are believed to l of the organic matter which was included in the rock at the deposition.

The Galena and Trenton formations in Wisconsin and jacent parts of Iowa and Illinois contain ores of lead and zinc,[1] mainly in the form of sulphides or carbonates. Lead ores are also found in the Ordovician (or Cambro-Ordovician) formations of southeastern Missouri,[2] and lead and zinc ores in the south-central part of the same State. In all these regions the lead and zinc ores occur (1) in cavities formed by solution, (2) as replacements of limestone, or (3) in veins.

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[1] Dana's Manual of Geology, 1895.

[2] See Orton, 8th Ann. Rept. U. S. Geol. Surv.; Phinney, 11th Anr the reports of the State Geol. Surv. of Ohio and Indiana.

The manganese ore of Arkansas is associated with the Ordovician formations.[3]

The Ordovician limestones of central Tennessee locally yield phosphates, much used as fertilizers. The workable deposits have resulted from the leaching of phosphatic limestone, and the concentration of phosphatic material [4] (Fig. 154.) The metamorphic Ordovician limestones of New England and some parts of the Appalachian mountains have been extensively used for marble.

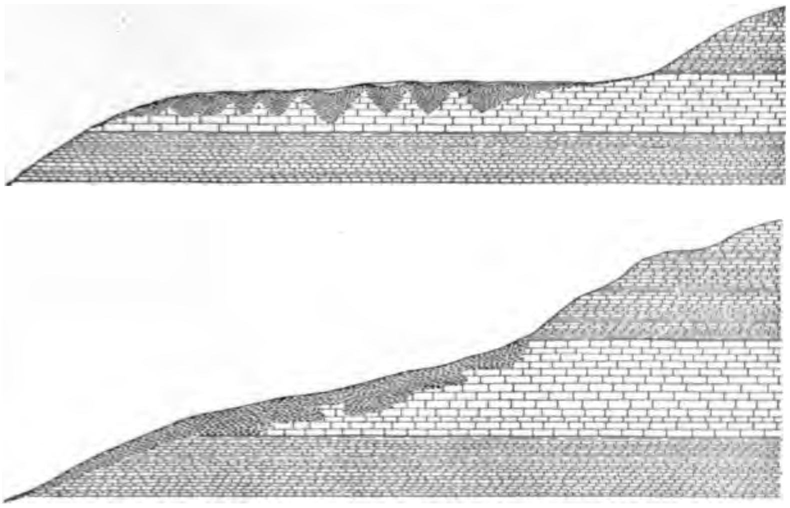

Fig 154.—Shows the modes of occurrence of the phosphates (the shaded surface parts of the limestone) in central Tennessee. (Hayes and Ulrich, Columbia (Tenn.) folio, U. S. Geol. Surv.)

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[1] See Chamberlin, Geology of Wisconsin, Vol. IV, pp. 365–568; and Calvin and Bain, Iowa Geol. Surv., Vol. VI.

[2] Winslow, Missouri Geol. Surv., Vol. VI and VII.

[3] Penrose, Ann. Rept. Arkansas Geol. Surv., 1890, Vol I.

[4] Hayes, Columbia (Tenn.) folio, U. S. Geol. Surv.

FOREIGN ORDOVICIAN.

The Ordovician formations appear at the surface in various pa Europe, and they exist concealed by younger formations over con able areas where they are not seen. Fig. 155 represents the g

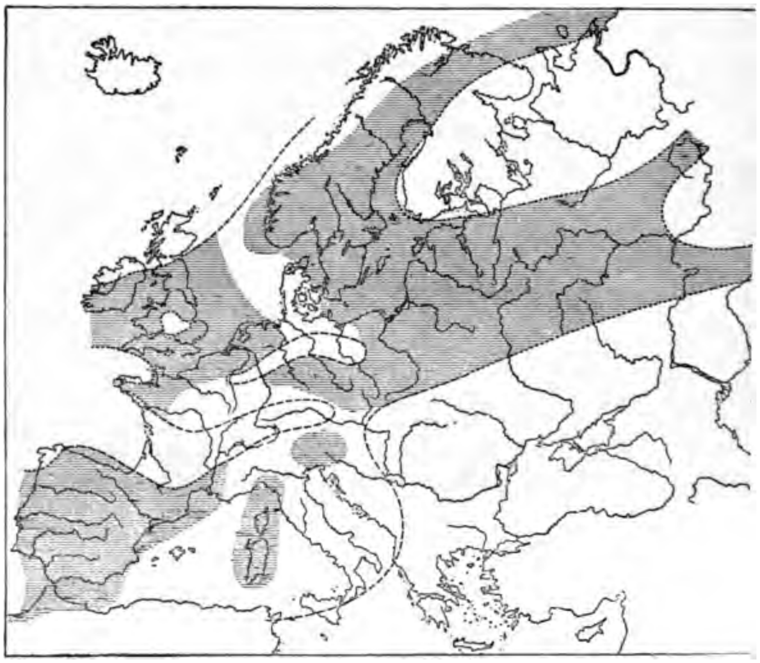

FIG. 155.—Diagram showing the relations of land and water in western Eu the Ordovician period. The shaded parts represent areas of marine sedime (After DeLapparent.)

geographic relations of land and water in Europe during this p The submerged area represents in a general way the area whe Ordovician formations are present.

The known formations of this system, like those of the Cam are divisible into two geographic provinces, a northern and a sou The line or belt which separates them runs from the English C on the west, across the plains of Germany to the heart of Rus the east. To the northern province belong the Ordovician str the British Isles, Scandinavia, and Russia. To the southern

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[1] DeLapparent, Traité de Géologie, quatrième edition, p. 809.

the corresponding formations of Bohemia, southern Germany, France, Switzerland, Spain, and Portugal.

The basis for the separation of the system into two geographic parts is found primarily in the fossils, which are notably unlike in the two provinces, and partly in the nature of the rocks themselves. The north European faunas were more closely allied to those of Asia and North and South America, and were the more general or cosmopolitan; the south European faunas were more local and provincial.[1] An illustration of the wide distribution of certain pelagic faunas is furnished by the graptolites. Of 59 species from the Skiddaw slates (Lower Ordovician) of north England, 14 are common to other parts of Britain, 25 to the Quebec group (Lower Ordovician) of Canada, and 34 to the Ordovician of Sweden.[2]

The strata of the northern province, except in the British Isles, are essentially horizontal, while those of the southern province are much more generally disturbed. Where much disturbed, they have been notably metamorphosed in both the northern and southern provinces.

In keeping with the attitude of the strata, the outcrops cover larger areas in the northern province than in the southern. The most extensive outcrop is in the Baltic region of Russia. The Ordovician beds of this region are probably continuous beneath later formations with the Ordovician of the Ural mountains, and the system probably underlies all of northern Russia.[3] Not only does the system nowhere appear at the surface over large areas in southern Europe, but there is some indication that the outcropping formations of different regions are not continuous with one another beneath younger beds.

The formations of the European Ordovician are largely fragmental, being made up of shales, sandstones, graywackes, etc., with which there is associated relatively little limestone. Where the latter occurs, it often has the form of great lenses interbedded with clastic rocks, showing that conditions favorable for its formation were not continuous over great areas. In its paucity of limestone, the Ordovician of Europe is in contrast with that of North America. The constitution of the system as a whole is such as to show that sedimentation was very varied within the area of Europe. The succession of beds is often markedly different in closely associated localities, and even divisions established for the northern province do not hol southern.

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[1] Kayser, Geologische Formationskunde, zweite Auflage.

[2] Geikie, op. cit., p. 949.

[3] Geikie, op. cit., p. 968.

The Ordovician system was first differentiated in Gre where it was described under the name of Lower Silurian which is still frequently applied to it. The name here us system, which comes from the region occupied by the Ord relatively recent adoption.[2]

The system is represented in the British Isles by great of strata (something like 24,000 feet maximum).[3] Loca nearly half the system is composed of igneous rock of sheets of lava and beds of fragmental igneous rocks sorts. In the north of England, the successive beds of i partly lava-flows and partly tuffs, not interstratified w sediments except near the base and summit, suggest that took place, in part at least, on land. In Wales, on the the igneous rocks are interstratified with sedimentaries, a fore thought to have been ejected beneath water.[4] T the most extensive, as well as one of the most ancient, of Europe. Igneous rocks of Ordovician age also occu of Ireland.

From north England and Wales the system thins in though it has a thickness of something like three miles i highlands of Scotland. The figures given are to be l maxima, not as averages. In Scandinavia and Rus has but a fraction of the thickness which it possesses the strata are essentially horizontal. About the Gulf o of the Ordovician beds of clay and sand are still uncon sands and clays of the system here might be taken, so f characteristics go, for Tertiary.

In the southern province of Europe, as in most the Ordovician system does not attain great thicknes is there more abundant than in the north. The st about various mountains where local disturbances

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[1] Murchison, Phil. Mag. and Brit. Assoc., 1835.

[2] Lapworth, Geol. Mag., 1879, p. 13.

[3] This measurement is doubtless subject to the qualificatio

[4] Geikie, op. cit., pp. 946 and 949.

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uropean continent, on the other hand, orogenic disturbances ot appear to have taken place at the close of the Ordovician. urope, as in America, the great disturbances took place where th odies of sediment had been accumulated, or else the beds w eatly thickened by the disturbances.

The Ordovician system of Europe, like that of America, is divi to several groups of strata, but it is impossible to correlate th ibdivisions with those of North America with anything like ac cy. In Great Britain the four principal divisions, beginning w ie oldest, are (1) Tremadoc, (2) Arenig, (3) Llandeilo, and (4) Ca oc or Bala.

In other continents the Ordovician strata have usually not b parated from the overlying Silurian, but they are known to hav ide distribution in the Arctic regions (Kennedy Straits, Bootl ornwallis, Griffith, North Devon, East coast of Greenland, etc.). uth-central Siberia they are said to be represented by red beds, w lt and gypsum.[1] In northern China, the Ordovician system is rep nted by 3000 to 4000 feet of limestone, which overlies the Up ambrian conformably.

CLIMATE.

Neither in Europe nor in America is there decisive evidence t imatic zones were distinctly marked. All that is known of the this era would seem to indicate that the climate was much m iform than now throughout the areas where the strata of the pe e known. The fact that the Ordovician rocks have been identi the far north (in North Devon, the west coast of King Willia and, Boothia, etc.) by their fossils, indicates that the climatic c tions of North America and Europe must have been less diversi an now.

ORDOVICIAN LIFE.

Close sequence upon the Cambrian.—To the fact that no gr hysical change took place in the passage from the Cambrian to rdovician deposits, as usually defined,[3] is now to be added the c relative fact that there was no distinct break in the succession of life. All reasonable doubt that the continuity between the two periods was real and not merely apparent is thus removed, for had any great interval been left unrecorded by the deposits, it must have made itself manifest by a break in the continuity of the life. There seems ample warrant, therefore, for the view that the vast period from the beginning of the Cambrian to the close of the Ordovician was one long eon of progressive development and of expansion of life, and that its division into two nominal periods is artificial rather than natural.

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[1] De Lapparent, op. cit., p. 807.

[2] Blackwelder, Carnegie Institution. Unpublished evidence.

[3] Were the dividing plane placed at the unconformity above the Calciferous (B antown of the east, Lower Magnesian of the Upper Mississippi Valley), an ap able change in the life would have to be recognized, but it would not be a ra ie. For North America, the plane of the unconformity appears to be the b ividing horizon.

Edaphic, Provincial, and Cosmopolitan Development.

Nevertheless, the life progress was not uniform in all regions, though in its general aspect it was cosmopolitan. It varied much as the continental evolution varied, and largely as the result of it. The variations assumed three general phases: (1) adaptation to the immediate physical environment, particularly the nature and depth of the sea-bottom (edaphic adaptation); (2) modification by self-evolution within restricted areas where isolated from other regions by barriers (provincial evolution), and (3) modification toward a universal type through the intermigration of the life of various regions when barriers were removed (cosmopolitan development).

(1) **Edaphic modification**.—Areas in which the bottom was rocky, or sandy, or muddy, or calcareous, had their appropriate life, as did also the tracts of shallow and deep water, and the areas dominated by other special conditions. The assemblages adapted to these special conditions were not entirely distinct from one another, for there were not a few forms that were indifferent to these conditions, particularly the floating and free-swimming species; but the aspect of the fauna, particularly the sea-bottom portion of it, was locally modified. These modifications are well shown in the Ordovician fossils, but they are of too intricate a nature to be set forth specifically here.

(2) **Provincial modifications.**—Although for the greater part the sea was spread widely upon the face of the continent in Ordovician times, and the facilities for the intermigration and mingling of faunas were usually excellent, there is evidence of considerable separation into zoölogical provinces. This was probably due in the main to barriers interposed by gentle warpings of the sea-bottom which introduced emergent tracts and tracts of excessive depth; but probably also in

rt to barriers constructed by the sea itself, in the form of shoal rs and spits. In some cases the separation of the provinces m ve been due to nothing more substantial than sea-currents and t tendant differences in temperature, or to locally increased or lessen linity of the waters. The formation and shifting of provinces due rface warpings seems to have been most marked in the Appalachi ct, where deformations have been more pronounced than in t terior in most geological stages. Some notable progress has recent en made in working out these provinces, but the delineations ha t yet been brought to sufficient completeness and sureness to warra attempt to sketch them here.[1]

(3) **Cosmopolitan development.**—Notwithstanding the local a ovincial modifications just named, the progress of the Ordovic e on the American continent seems to have been, on the whole, e direction of cosmopolitanism. This was due, in part, to the wi velopment of the epicontinental seas, which in themselves gave oad and rich field for evolution, and in part to the facilities for t termingling of the faunas of the various continents. A cosmopolit ndency is particularly marked in the great interior region which w re stable than the border tracts and which better discloses the gre es of biological movement, because less affected by the little ones.

The preceding statements relate chiefly to the shallow-water life e sea, as this includes the larger part of all that is represented ose portions of the deposits that are now accessible. The deep-s ds of the Ordovician are nearly all, probably quite all, inaccessib e shallow-water life that was subject to local and regional modificati braced not only the species which were limited to particular kin bottom, etc., but those which were dependent on these for food a other necessary conditions of life.

Fortunately, however, in the Ordovician deposits there is an exce nal record of the free-floating life of the ocean made by an extin ler, the *graptolites* (Fig. 167).[2] This record is not, however, isolate it might have been if deposited on a sub-oceanic plateau in mi ean, inaccessible to coast life, and covered with water too shallow f abysmal life. The graptolites are mingled more or less freely with the fossils of the shallow-water life. This implies that the open-sea life was borne freely over the epicontinental seas. This is further testimony to the sea-prevalence and the cosmopolitan tendency of the life development. Pelagic forms in general enjoy great freedom of distribution, and hence their progress is to be presumed to be much the same in all oceanic regions. Even here, absolute equality of progress is not predicable, for the ocean-currents form circuits within which they return upon themselves without compassing the whole globe, and without commingling very extensively with other waters; and hence even the floating open-sea life is assembled in some measure into vague provinces, and this has probably always been the case. But the Ordovician graptolites are found to be practically identical not only on the European and American sides of the North Atlantic, which might have been dominated by an oceanic circuit of its own, but in the seas of the times as far away as Australia, whose relations are with the Pacific, the Indian, and the Antarctic oceans. The inference is that the range of the graptolite species was ocean-wide. They were *par excellence* cosmopolitan forms. Lapworth[1] has shown that the duration of individual species was not very great, geologically speaking, and hence the succession of species was well suited to mark the contemporaneous progress of events in all quarters of the ocean. During the lifetime of the graptolites, which unfortunately was limited to the late Cambrian, Ordovician, and Silurian, Lapworth identifies a score of successive zones, each characterized by a particular species. One of these zones falls in the Cambrian, eight in the Ordovician, and eleven in the Silurian. If these be taken as chronological bench-marks, so to speak, the successive horizons of the different continents may be accurately correlated and the progress of life in the various quarters of the globe referred to a common set of standards. The succession of American faunas will claim our attention later. Our first concern is with the general progress of life.

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[1] See Paleozoic Seas and Barriers, by E. O. Ulrich and Charles Schuchert, Re Y. State Paleontologist, 1901, pp. 633–658.

[2] It is not universally agreed that all graptolites were floating forms at all stag there seems to be little doubt that they usually were in their young stages at lea

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[1] On the geological Distribution of the Rhabdophora, Ann. Mag. Nat. Hist., 5th Ser., Vol. III, pp. 245, 445; Vol. IV, pp. 333, 418; Vol. V, pp. 45, 149, 273, and 358; Vol. VI, pp. 16, 185. On American graptolites, see particularly James Hall, Can. Org. Remains, Dec. II, 1865; 20th Rept. N. Y. State Cab. of Nat. Hist., 1868; R. R. Gurley, Jour. Geol., Vol. IV, 1896, pp. 63 and 291, and R. Ruedemann, Mem. No. 7, N. State Mus.

THE GENERAL PROGRESS OF ORDOVICIAN LIFE.

While there was a fair preservation of the life of the Can there is a much superior representation of the Ordovician life. part of this is due to a real advance in fossilizable forms, and pr to a real multiplication of their numbers, but a part is probab due to better conditions of preservation. The Ordovician life is ably to be regarded as the climax of the life of the first great iferous period, and as such its fossils may well receive more and fuller illustration relatively than it will be possible to giv faunas.

The Scantiness of the Record of Land Life.

Theoretically, there are strong reasons for believing that th dophytes and perhaps other leading groups of plants clothed th for they appear in abundance, in high development, and in wide entiation in the Devonian period. The physical argument for a clothing of the land is also now stronger than before, for ani swarmed about the shores, and limestone was sometimes lai close to the Archean crystalline rocks and even among the hills, as in Ontario and elsewhere. This is difficult to unders the crystalline rocks were naked and the wash from them unres even if their surfaces were rather low. Rather should we expect sandstones in all the adjacent tract and relative scantiness because the land waters would be poor in organic matter if t bore no vegetation. If on the other hand the land were cloth vegetation and relatively low, silty wash would be limited, t waters rich in organic matter, and the conditions favorable for teeming life near the shores, and free limestone depositi consequence. But the record merely furnishes some imperfe that are interpretable as land plants, without revealing much land vegetation.[1]

The first record of insect life.—The oldest relic of insect life at present is a rather obscure wing found in the graptolite of the Upper Ordovician of Sweden. It is referred to the c Hemiptera (bugs, cicada, etc.). Not enough is preserved t fully the insect's nature, but the existence of any flying insect order implies the presence of vegetation and of atmospheric conditions suited to active, air-breathing organisms.

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[1] Dawson, Plant Life, p. 21.

The Main Record Marine.

The marine invertebrates made up almost the whole of the recorded fauna of the Ordovician, and among these the trilobites, the cephalopods, and the brachiopods held the leading places. Of these, the brachiopods were the most numerous, the trilobites the highest in organization, and the cephalopods the most powerful. But the foreshadowings of a new dynasty were even then at hand.

The appearance of the vertebrates.—In the Ordovician near Canyon City, and at some other localities in Colorado, the remains of fish-like organisms occur in great abundance, but, unfortunately, in poor condition, associated with characteristic Ordovician invertebrates.[1] The fish relics are very fragmentary, but among them there are complete dermal plates. Rarely, a few of these plates remain joined to one another. There are also portions of the vertebral column. The relics are sufficient to make it clear that fish-like forms lived in some abundance, and that they were armed for defense. It is not equally clear that they were armed for attack.

The climax of the trilobites.—More than half of all the known genera of trilobites, as listed by Zittel, were represented in Ordovician times. Only a few of these came over from the Cambrian, while the others make their first appearance in this period. In the next period (Silurian), their numbers fell to one half, and in later periods declined still further until they disappeared at the close of the Paleozoic era. The rise and fall of the trilobites is shown graphically in the curve of the accompanying figure (Fig. 156). Their climax appears to have been reached by a rapid evolutionary ascent, and to have been followed by a more gradual decline, but the ascent was doubtless very much more prolonged in reality than appears from the record, which is doubtless less complete in the Cambrian and pre-Cambrian systems than in those of later periods. The attainment of a climax so early in the recorded history of life is a very notable event.

The cystoids and the graptolites also reach their climaxes in this period. The cystoids were, however, replaced by their near kin, the crinoids, and the much simpler organization of the graptolites makes their early climax less significant. The climax of the trilobit therefore be regarded as the foremost great event of its kind definitely recorded.

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[1] Walcott, Bull. Geol. Soc. of Am., Vol. III, pp. 153-171.

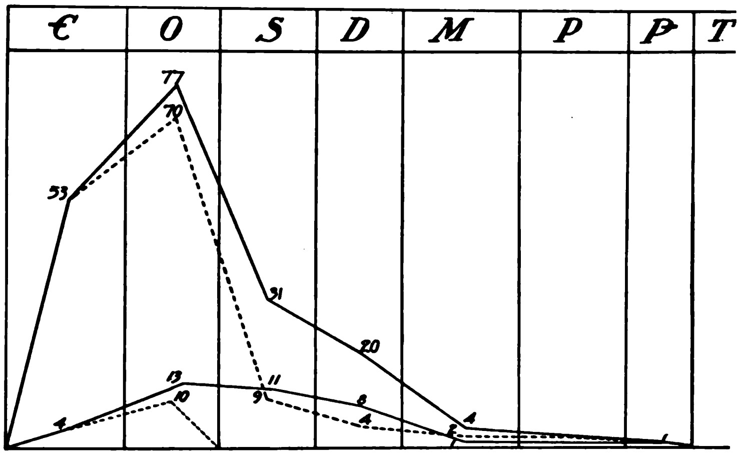

Fig. 156.—The two upper curves represent the history of the trilobites to genera, the full line indicating the total number of genera present in t of the successive periods, and the dotted line the number of new genera in The two lower curves present the same data for the families of the trilc full line representing the total number of families present, and the d the number of new families introduced. The data for the families is ta Beecher in the Zittel-Eastman text-book of Paleontology, Vol. I. The the genera is somewhat incomplete, but is as full as can be made fro "Handbuch der Palæontologie."

The general aspect of the trilobites at the high tide of thei is fairly illustrated in the group shown in Fig. 157. The Or trilobites were usually much better preserved than their C predecessors, but still they are never known to have been fossilized. So general was the loss of the more fragile par the nature of the appendages and of the under parts was a question until recent years, when the under-structure was out in the case of a few forms by the skill and patience of Beecher, and others.[1] These few forms doubtless represent the nature of the appendages of the whole order, though notabl tions are not improbable. The accompanying photograph of

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[1] Walcott, 28th Rept. N. Y. State Mus. Nat. Hist., 1875; Bull. Mus. Co Cambridge, VIII, 1881. Beecher, Am. Jour. Sci., Vol. XLVI, 1893; Vo 1894, and Vol. I, Ser. 4, 1896; Am. Geol., Vol. XIII, 1894, and Vol. XV, 18 thew, Am. Jour. Sci., Vol. XLVI, 1893. (Weller).

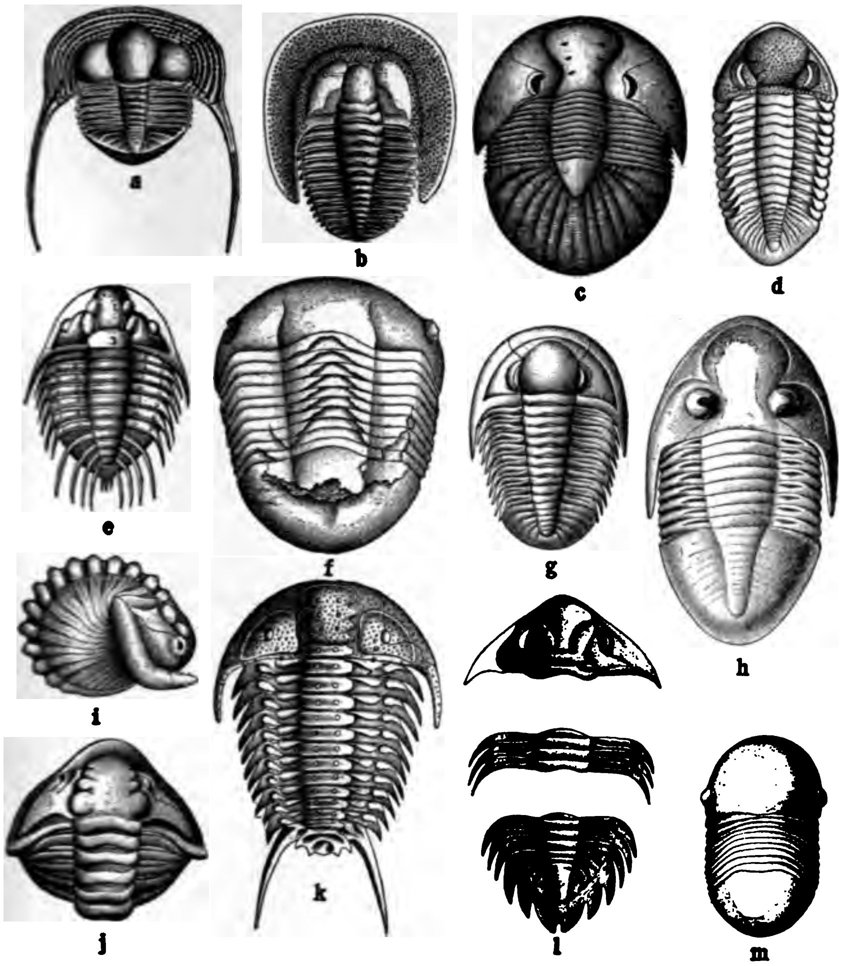

Fig. 177.—*Ordovician Trilobites.* *a*, *Trinucleus ornatus* Sternberg; *b*, *Harpes primus* Barrande; *c*, *Bronteus lunatus* Billings; *d*, *Pterygometopus callicephalus* (Hall); *e*, *Odontopleura crosotus* (Locke); *f*, *Illænus americanus* Billings; *g*, *Pröetus parviusculus* Hall; *h*, *Isotelus maximus* Locke; *i–j*, *Calymene callicephala* Green; *k*, *Ceraurus pleurexanthemus* Green; *l*, *Lichas incola* Barrande; *m*, *Bumastus trentonensis* (Emmons). The lowest order of Trilobites, the Hypoparia, are represented by figures *a* and *b*. They have no true eyes, and the facial suture is marginal or sub-marginal. Figures *e, f, g, h, l,* and *m* are examples of the trilobite order Opisthoparia, in which the posterior limb of the facial suture is directed backward, cutting the posterior margin of the head and leaving the genal angle on the free cheek. The different degrees of differentiation of the glabella should be noted. Figures *d, i–j,* and *k* are examples of the order Proparia which includes the highest of the trilobites; the posterior limb of the facial suture is directed laterally, leaving the genal angle upon the fixed cheek; this order was not present in the Cambrian faunas.

by Beecher (Fig. 158), made by combining parts of different viduals of *Triarthus beckii*, shows that this species possessed of legs extending along each side of the body and that these wer nished with fringed natatory branches. From these appendag is inferred that the *Triarthus* both ran and swam and was a swift animal. It possessed antennæ, which probably signifies a well-deve tactile sense. The swimming filaments have not been found in genera where the legs have been observed. In these cases it is

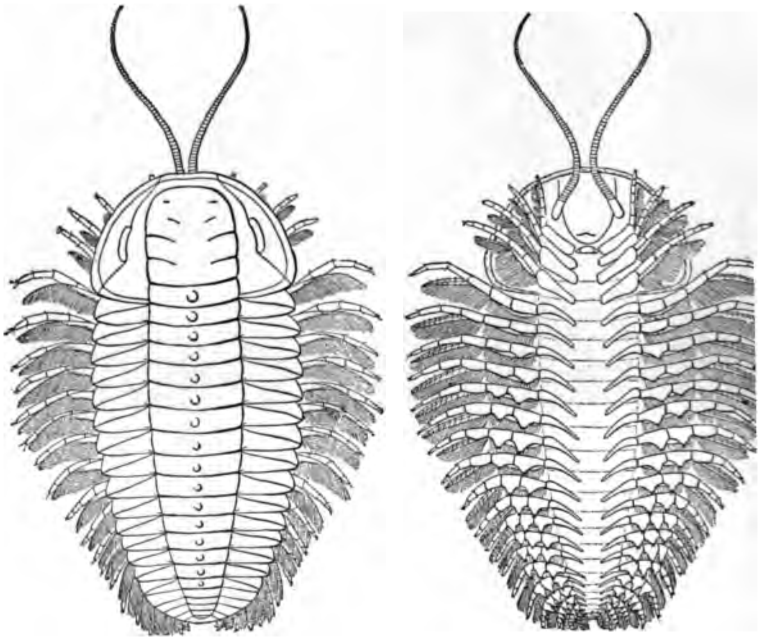

FIG. 158.—*Triarthus beckii* Green, showing the locomotive and other append Dorsal and ventral aspects. (After Beecher.)

that the legs are relatively weak, and that these are forms whic the habit of rolling up, while the *Triarthus* was stiffly articul The suggestion has hence been made that the trilobites followed lines of development. The one class, being weak in power of motion and sluggish in habit, developed a jointed articulation found safety when attacked in rolling up armadillo fashion, whil other acquired effective running and swimming organs and f safety in flight; but present data are insufficient to demonstrate distinction, for the appendages of most trilobites are still unkn

The eyes of the Ordovician trilobites, as a rule, were more prominent and better developed than those of the Cambrian forms, and showed improved adaptation by being set on a curved pedestal, so that some eyelets were directed more to the front and others more to the rear, giving an ampler angle of vision (see particularly *d* and *h*, Fig. 157). There was little or no increase in the average size of the trilobites. The *Isotelus gigas* sometimes reached a length of 18 inches and ranked among the giant trilobites, but it was equaled and even surpassed by some of the great *Paradoxides* of the Cambrian. Progress took the form of improvement of the parts and of superior adaptation rather than increased size. Curious ornamentation of the exterior was displayed in some genera, as were also eccentric departures from the simple three-lobed form, but such aberrations became far more pronounced in the early stages of the decline of the trilobites, in later periods.

Other crustaceans.—Besides the trilobites, the crustaceans were represented by a few inferior forms. Ostracodes were common in some beds (Fig. 159, *a*, *b*, *c*, *d*, *e*, *f*, *g*, and *h*) and there were a few cirripeds of which the barnacle is the most familiar modern type; but, unlike the barnacle, the Ordovician cirripeds had an elongate body and were not sessile (Fig. 159, *i*, *j*). The euripterids, a limuloid form related to the arachnids, appeared in the later part of the period.

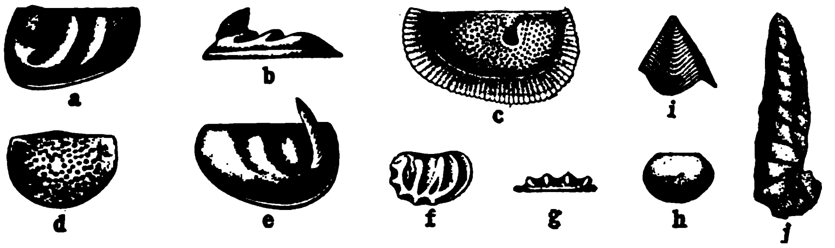

FIG. 159.—*Ordovician Crustacea*, other than Trilobites. *a–b*, *Ceratopsis oculifera* (Hall), lateral and ventral views; *c*, *Eurychilina reticulata* Ulrich; *d*, *Macronotella scofieldi* Ulrich; *e*, *Ceratopsis chambersi* (Miller); *f–g*, *Tetradella quadrilirata* H. and W., lateral and dorsal view; *h*, *Aparchites minutissimus* Hall; *i–j*, *Lepidocoleus jamesi* (Meek), a single plate and a complete individual. Figures *a–b*, *c*, *d*, *e*, *f–g*, and *h* are examples of Ordovician ostracods, all of them much magnified. Figures *i–j* are illustrations of a single plate and of the complete individual of a cirriped crustacean.

The dominance of the cephalopods.—The largest, the most powerful, and perhaps the most predaceous of the known forms of Ordovician

life were the cephalopods, which seem to have come in with ext
dinary suddenness. Unless the fishes, of which so little is kn
contested their supremacy, they were doubtless the undisputed ma
of the sea. Their relics first appear at the time of the transition
the Cambrian to the Ordovician, but they were then so far adva
in their development and so widely differentiated from allied forms
render it probable that they had really lived much earlier.
general aspect may be gathered from the group in Fig. 160, but

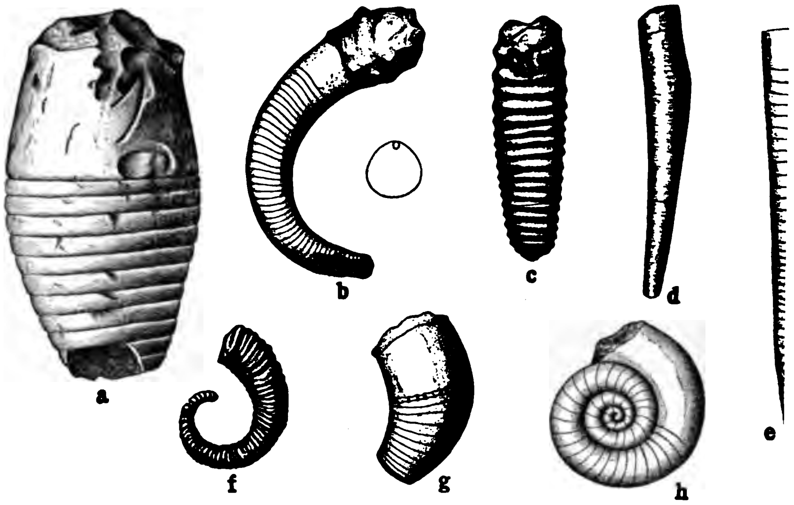

FIG. 160.—*Ordovician Cephalopods. a, Poterioceras apertum* Whiteaves; *b,*
ceras neleus Hall; *c, Orthoceras bilineatum* Hall; *d, Clinoceras mumi*
(Whitfield); *e, Orthoceras sociale* Hall; *f, Gyroceras duplicicostatum* Wh
g, Oncoceras pandion Hall; *h, Trocholites ammonius* Conrad. These figures ill
different types of Ordovician cephalopods, varying from the straight ort
tites (*e*) to the closely coiled nautiloid type (*h*). In all of them however, the
are straight or nearly so. (Weller.)

small forms, or large forms on a greatly reduced scale, are ava
for illustration. The dominant form, as well as the most prin
one, was the *Orthoceras* (Fig. 160, *e*), whose shell consisted of a
straight, gently tapering cone, partitioned by plane septa into cha
connected by a central tube (siphuncle). Even in Ordovician
there had already been a wide departure from the ideal simplic
the *Orthoceras*. There were not only moderate curvatures, as
plified by the *Cyrtoceras* (Fig. 160, *b*), but there were loosely
forms as the *Gyroceras* (Fig. 160, *f*) and close-coiled ones, as the

cholites (Fig. 160, *h*), which resembled the *Nautilus* of to-day. The straight forms preponderated, however, and the sutures scarcely departed from severe simplicity. We shall find that in later periods the septa and other features varied still more widely, and by so doing marked, in a very tangible way, the progress of the class.

Perhaps no other invertebrates so well show the progress of Paleozoic and Mesozoic times as the cephalopods, and this invites a special study of these early forms. The size attained in this early period was probably as great as ever reached by the chambered cephalopods, some of the shells being twelve or fifteen feet in length and a foot in greatest diameter. From this maximum they ranged down to forms smaller than a pipe-stem. Their habits are wholly matters of inference from their structure, and from the habits of their relatives in the present seas. Perhaps they floated, shell uppermost, or crawled upon the bottom, and preyed upon a variety of weaker forms of life.

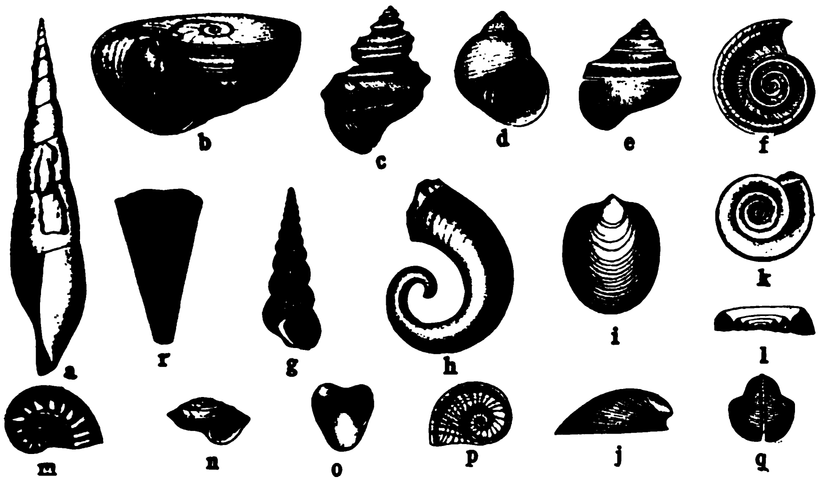

FIG. 161.—*Ordovician Gastropods.* *a*, *Subulites regularis* U. and S.; *b*, *Maclurea logani* Salter; *c*, *Lophospira helicteres* (Salter); *d*, *Cyclonema bilix* (Conrad); *e*, *Schizolopha textilis* Ulrich; *f*, *Helicotoma planulata* Salter; *g*, *Hormotoma gracilis* (Hall); *h*, *Eccyliomphalus triangulus* Whitfield; *ij*, *Archinacella cingulata* Ulrich; *k–l*, *Ophileta complanata* Vanuxem; *m*, *Cyrtolites ornatus* Conrad; *n*, *Raphistomina lapicida* (Salter); *o*, *Protowarthia cancellata* (Hall); *p*, *Conradella fimbriata* U. and S.; *q*, *Bellerophon clausus* Ulrich; *r*, *Conularia trentonensis* Hall. The exact zoological position of Conularia (*r*) is not certainly known, but it is usually regarded as a pteropod. The remaining figures illustrate in a measure the great variety of forms assumed by the Ordovician gastropods, a remarkable amount of differentiation when the slight representation of the group in Cambrian faunas is recalled.

The Ordovician gastropods.—The gastropods were very f represented in the early Ordovician fauna. There were present only the simpler shell-forms, which consist merely of a low cone w vertical or slightly curved axis, like the capulids (Fig. 161 *i*, *j*) also the three leading types of the spiral shell, the depressed cor coil (Fig. 161, *k*, *l*), the low spire (Fig. 161, *n*) and the elevated spire 161, *g* and *a*). The last made a relative gain as the period progre Perhaps no form of early Paleozoic life so closely and so obvi resembled the modern forms as the gastropods, which even the structed recognize as "snails." The *Conularia* (Fig. 161, *r*) repre the suborder pteropods.

The Ordovician pelecypods.—The pelecypods (lamellibranchs) their representatives (the clams) of to-day, seem to have been fo muddy or sandy bottoms, for they are rather rare in the lime

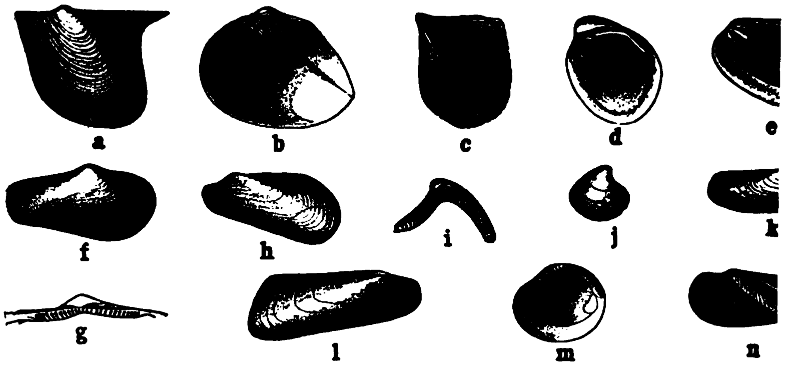

FIG. 162.—*Ordovician Pelecypods* (Lamellibranchs). *a*, *Pterinea demissa* (C exterior of left valve; *b*, *Lyrodesma cincinnatiensis* Hall, interior of right showing a primitive type of hinge; *c*, *Byssonychia radiata* (Hall), exterior valve; *d*, *Vanuxemia dixonensis* M. and W., interior of right valve, showi hinge and muscular impressions; *e*, *Ischyrodonta decipiens* Ulrich, inte right valve, showing the hinge and muscular impressions; *f–g*, *Ctenodonta* (Hall), exterior of right valve and a view of the hinge; *h*, *Modiolopsis arguta* (I exterior of the left valve, and a view of the hinge; *i–j Ctenodonta recurva* exterior of right valve and a view of the hinge; *k*, *Rhytimya radiata* exterior of the right valve, *l*, *Orthodesma rectum* H. and W., exterior of th valve; *m*, *Ctenodonta pectunculoides* Hall, interior of the left valve, showi hinge; *n*, *Technophorus divaricatus* Ulrich, exterior of the left valve. usually described as a pelecypod, but it is probably a peculiar bivalve crus

beds of the earlier and middle Ordovician, but increase in abun as the deposits grade into the shales of the later Ordovician. C whole they were very subordinate to the gastropods and cephal in numbers and in range, except locally. This is perhaps the notable, as the pelecypods are the lower and less differentiated type, though the hinged double valve is a device of higher order than the single valve. Representative forms are shown in Fig. 162.

The abundant development of the brachiopods.—Shells of brachiopods are the most common fossils of the Ordovician strata. This arose no doubt partly from their special suitability for preservation; but chiefly, we may safely assume, from their numerical superiority in the Ordovician fauna. The record, as it now stands, shows more individuals per species than in any other class except perhaps the bryozoans. This wide deployment is the more notable since the brachiopods were among the most conservative of all the classes found in the fossil state. The lower inarticulate forms of the order, which predominated in the Cambrian, continued through the Ordovician (as indeed they have done to the present time), but the higher articulate forms greatly outnumbered them. The large development of the articulate class was attended by a progressive evolution of the mode of articulation in which two lines were followed. In some the length of the hinge was increased, apparently affording a better means of resisting the attempts of their enemies to reach them by sliding or rotating the valves past one another (see Fig. 163, *a*, *b*, *e*, *f*, *g*, etc.). In others the front of the shell opposite the hinge was notched so that the valves were interlocked when closed, and thus more effectively resisted any sliding upon one another (Fig. 163, *d* and *u*). This device was usually best developed in the shells of narrow and weak hinge-line, where it was most needed (Fig. 163, *t*–*u*). Some shells combined both the long hinge-line and the interlocking front (Fig. 163, *c*–*d*). The hinges themselves were also improved by the use of different adaptations, not easily described briefly, but illustrated measurably in Fig. 163, *b*, *e*, *g*, and *q*. In addition to these devices for preventing the opening of the shell, there was generally a thickening of the shell walls, and in many cases a ribbing of the exterior which gave strength without needless weight, and at the same time facilitated the crenulation and interlocking of the front edge (Fig. 163, *d* and *u*). Correlated with these developments was also a deepening and strengthing of the muscular impressions, which implies a stronger and better muscular system (Fig. 163, *b*, *e*, *g*, and *i*). The introduction of the brachidium (Fig. 163, *z*), a calcareous support for the fleshy arms, is another notable advance.

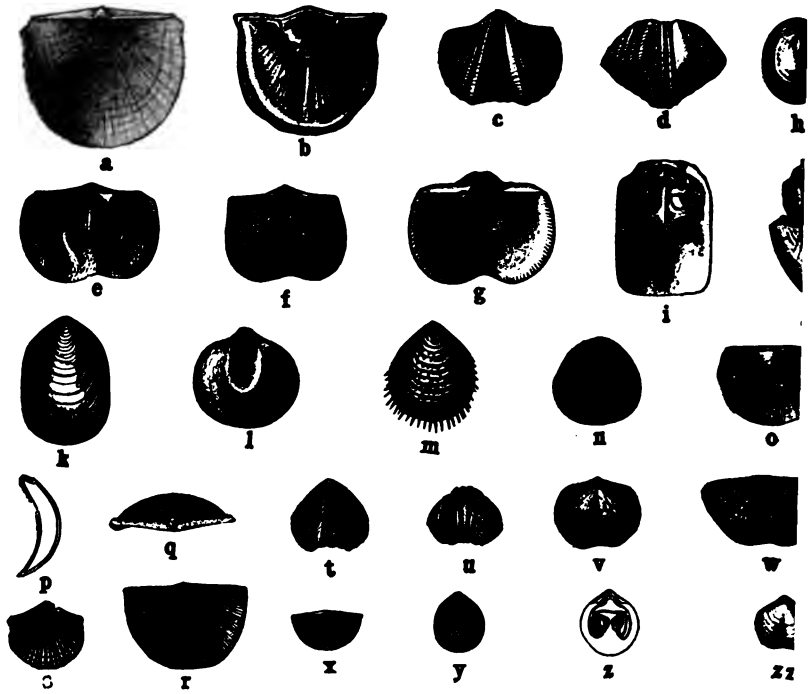

FIG. 163.—*Ordovician Brachiopods.* *a*, *Rafinesquina alternata* (Emmons), e
of the concave brachial or dorsal valve, with the cardinal area and tria
deltidium of the pedicle valve; *b*, *Clitambonites anomala* (Schl.), interior
pedicle valve, showing the spondylum; *c–d*, *Platystrophia lynx* (Eich.), e
of the pedicle valve and anterior view of a complete shell, showing the fol
sinus; *e–g*, *Hebertella sinuata* (Hall), interior views of the two valves (*e*=p
g=brachial), showing muscular impressions and hinge, and the exterio
complete shell from the pedicle side; *h*, *Schizotreta ovalis* H. and C.; the
valve; *i–j*, *Lingulasma schucherti* Ulrich, interior of the brachial valve, sh
the elevated platform for muscular attachment, and the median se
also a lateral view of an internal cast, showing the platforms in each
k, *Lingula rectilateralis* Emmons; *l*, *Trematis millepunctata* Hall, pedicle v
a complete shell, showing the unmodified notch-like pedicle opening; *m*,
treta fissus Kutorga, a pedicle valve much enlarged; *n*, *Schizocrania filosa* (
a brachial valve; *o*, *Crania lælia* Hall, brachial views of four indiv
attached to another shell; *p–r*, *Strophomena subtenta* Conrad, (*p*) profile
of the concavo-convex shell, (*q*) posterior view of a complete shell, showi
hinge-line, cardinal area, and deltidium, (*r*) exterior of the concave pedicle
s, *Orthis tricenaria* Conrad, exterior of the brachial valve and the cardina
of the pedicle valve, showing the open delthyrium; *t–u*, *Rhynchotrema*
Conrad, brachial and anterior views; *v*, *Dalmanella testudinaria* (Dal.), b
view; *w*, *Leptæna rhomdoidalis* Wilck.; the pedicle valve; *x*, *Plectambonite*
ceus (Sow.), brachial view; *y*, *Catazyga headi* (Bill.), brachial view; *z*, *Zyg*
recurvirostris (Hall), interior of a brachial valve, showing the spiral brachid
position; *zz*, *Zygospira exigua* (Hall), brachial view. Figures *h*, *i–j*, *k*, *l*,
and *o* are inarticulate brachiopods belonging to the orders *Atremata* and
mata, and serve to illustrate in a measure the great variety of these brach
in the Ordovician fauna. The remaining figures are articulate brachi
Protremata and *Telotremata*. Figures *y*, *z*, and *zz* are spire-bearing *Telot*
which first appear in this period.

A comparison of the accompanying figures with those of the Cambrian brachiopods will illustrate, in some degree, these evolutions. All these devices seem to imply that the enemies of the brachiopods had increased in effectiveness also, perhaps in somewhat like proportions. That they did not gain undue mastery seems to be implied by the abundance of the brachiopods. A curious form was the concavo-convex type (Fig. 163, *p* and *q*), in which the living space between the valves was reduced almost to a minimum. Perhaps this also was an adroit protective device in that it gave so much shell for so little meat that it was scarce worth while for their enemies to crush them.

The abundance of the bryozoans.—The bryozoans were akin to the brachiopods, but their external forms, their habits of life, and their modes of depositing their hard parts were so different as to mask their kinship in the fossil form. The bryozoans lived in colonies, connected by a common mantle which secreted calcareous material to form the base or skeleton of the colony. These secretions so closely resemble those of the corals that they have often been classed as corals, and differences of opinion still exist relative to certain forms, the *Monticulipora* for example.[1] Certain bryozoan colonies formed hemispherical masses much like those of certain corals (Fig. 164, *b*). Others assumed branching forms, resembling the ramose corals (Fig. 164, *h* and *i*), while still others formed networks spread over other fossils (Fig. 164, *c*, *d*). The individual pit-like cavities, or cells (Fig. 164, *c*, *g*, *f*, and *j*) occupied by the individual bryozoans are usually much smaller than the cups of the corals, though the smallest cups of the corals are not larger than the largest cells of the bryozoans.

Judging by the fossils, the bryozoans were very rare in the Cambrian fauna, and were not very conspicuous in the early Ordovician, but they became abundant in the middle and later portions of the period, when they contributed an important element to the rock-material. The branched forms predominated, but the hemispherical and reticulated forms were not uncommon.

The deployment of the echinoderms.—While there is little more than a bare indication that the echinoderms were present in Cambrian time, before the close of the Ordovician period the cystoids had mounted to their climax, the crinoids had become prominent, and he asteroids, the ophiurians, and the echinoids had made their app nce, though scantily represented. This leaves unrepresented ne of the six classes susceptible of ready fossilization, the blasto nd even these were foreshadowed by the blastoidean character ome of the crinoids. Of all these, the cystoids were the most pr

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[1] "The Problem of the Monticuliporoidea," F. W. Sardeson, Jour. Geol., Vol. IX, 1901 pp. 1-27.

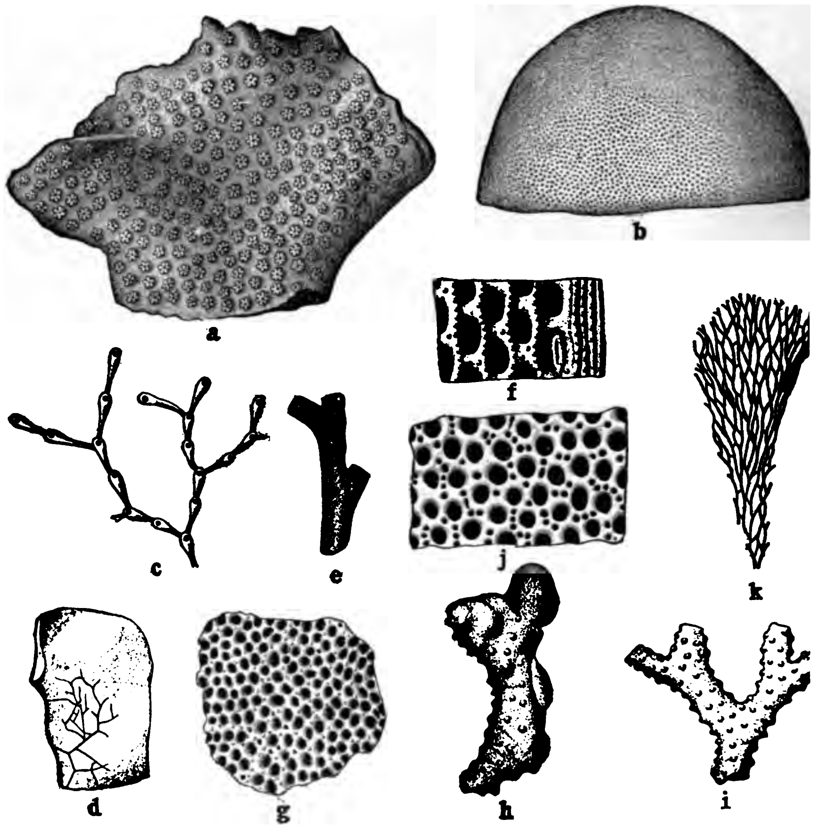


FIG. 164.—*Ordovician Bryozoans.* *a, Constellaria polystomella* Whitfield; *b, C pora hemispherica* Ulrich; *c–d, Stomatopora delicatula* (James); *e–f, Rhinid mutabilis* (Ulrich); *g–h, Monticulipora arborea* Ulrich; *i–j, Callopora pulc* Ulrich; *k, Phylloporina granistriata* Ulrich. These figures represent a fe the almost innumerable forms of bryozoans present in the Ordovician fa At times they contributed a large portion of the calcareous matter of limestones and calcareous shales.

tive in character and were doubtless most nearly like the parent s from which all were derived, if indeed the cystoids were not the an tral type. The irregular, unsymmetrical forms of the cystoids (Fig. *a–f*) were gradually replaced by the more symmetrical and be organized crinoids (Fig. 165, *g–n*). Starfishes and serpent-stars (Fig. 165, *o* and *p*) are familiar modern forms. The crinoids may be likened to starfishes turned face uppermost and fixed to the sea-bottom by a stem attached to the center of the back. The body was gathered into a cup-like form composed of close-fitting plates arranged in pentamerous symmetry, and crowned by a fringe of arms variously and often elaborately branched (Fig. 165, *g–k*). The upper surface of the body cavity was in many cases closed over by a "vault" or arch formed of similar plates. The whole, aptly styled the calyx, more closely

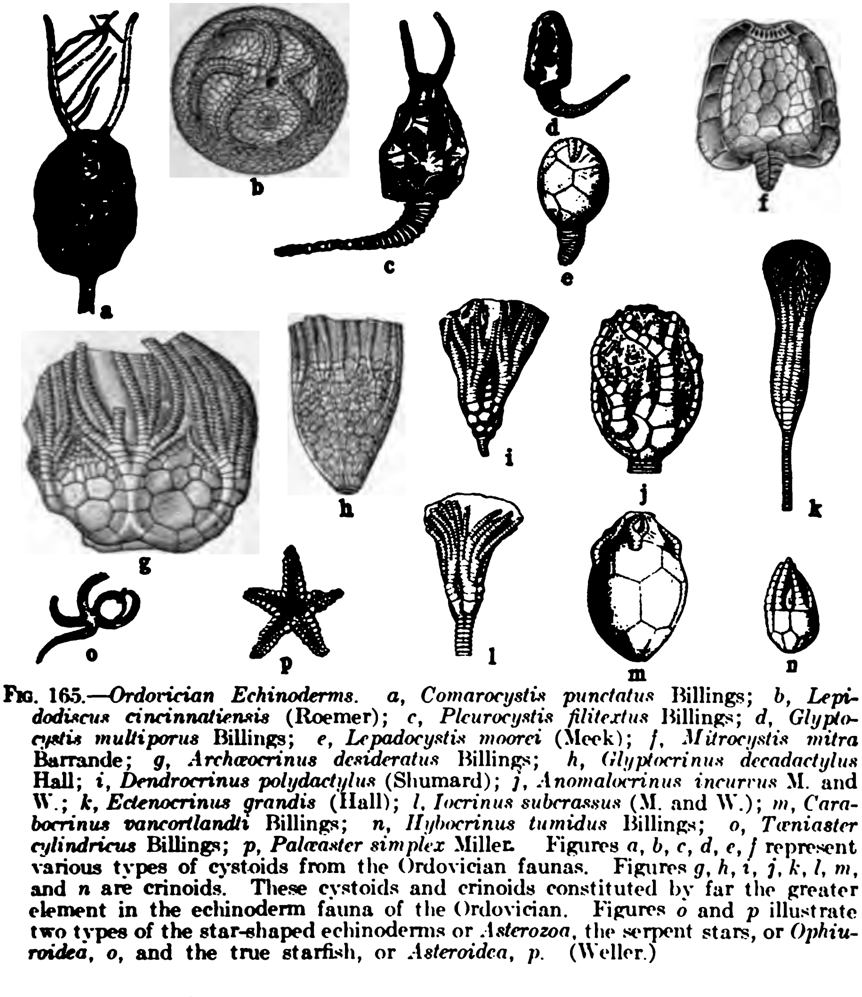


FIG. 165.—*Ordorician Echinoderms.* *a*, *Comarocystis punctatus* Billings; *b*, *Lepidodiscus cincinnatiensis* (Roemer); *c*, *Pleurocystis filitextus* Billings; *d*, *Glyptocystis multiporus* Billings; *e*, *Lepadocystis moorei* (Meek); *f*, *Mitrocystis mitra* Barrande; *g*, *Archæocrinus desideratus* Billings; *h*, *Glyptocrinus decadactylus* Hall; *i*, *Dendrocrinus polydactylus* (Shumard); *j*, *Anomalocrinus incurvus* M. and W.; *k*, *Ectenocrinus grandis* (Hall); *l*, *Iocrinus subcrassus* (M. and W.); *m*, *Carabocrinus vancortlandti* Billings; *n*, *Hybocrinus tumidus* Billings; *o*, *Tæniaster cylindricus* Billings; *p*, *Palæaster simplex* Miller. Figures *a*, *b*, *c*, *d*, *e*, *f* represent various types of cystoids from the Ordovician faunas. Figures *g*, *h*, *i*, *j*, *k*, *l*, *m*, and *n* are crinoids. These cystoids and crinoids constituted by far the greater element in the echinoderm fauna of the Ordovician. Figures *o* and *p* illustrate two types of the star-shaped echinoderms or *Asterozoa*, the serpent stars, or *Ophiuroidea*, *o*, and the true starfish, or *Asteroidea*, *p*. (Weller.)

resembled a flower in general aspect than an animal; and the fan name "sea-lily" is not inappropriate. Clad throughout in calcar plates, the crinoids were excellent subjects of fossilization save after the binding tissues decayed, the constituent plates easily apart and perfect specimens are rare. The stem, consisting of a s of disks ("little grindstones") perforated by a central canal, and dered flexible by a minimum of integument, was disjointed with e ease. Limestone is sometimes largely made up of crinoidal fragm

The structure of the cystoids (Fig. 165, *a–f*) was very simila that of the crinoids, but the body was unsymmetrical both in and in the arrangement of the plates. The outline of the cy was sometimes spheroidal or ovate, sometimes sac-like or club-sha sometimes depressed and disk-shaped, with irregular departures all these forms. A part or all of the plates were perforated by s pores connected with internal canals supposed to be concerne respiration, this being perhaps the most vital ground of distin from the crinoids, which do not usually show these. The arms few and irregular, and sometimes wanting; the stem usually and tapering, and often unattached.

Very little can be said regarding the evolution of the cystoid their forms are so heterogeneous and their functions so little k that it is not clear what constituted progress, and besides, they so scantily represented in the preceding period, and so soon dro away after the Ordovician, that an insufficient interval for compa is afforded. The rise of the crinoids and the displacement of the toids by them is doubtless to be regarded as a phase of progress. two classes lived in comparative abundance through the Ordov period, and on into the Silurian, but by the close of the latter p the cystoids had greatly declined, while the crinoids were in the h of their abundance.

The asteroids and ophiurians (Fig. 165, *o* and *p*) were not abu in the Ordovician, their chief development being reached much than that of the two preceding classes. The same is even more of the echinoids, which are barely represented in the strata of Eu

The development of the cœlenterates.—Corals were sparingly ent in the early part of the period, increased measurably in the m portion, and somewhat more markedly toward the close, but were not at any time a very prominent factor in the fauna. Fo greater part they belonged to the simpler horn-shaped type (Fig. 166, *a*, *b*, and *c*). Compound corals, formed by colonies of polyps living together, were present (Fig. 166, *d* and *e*) and rarely formed reefs. The hydrozoan branch of the cœlenterates was represented by *Stromatopora*, which deposited thin films of calcium carbonate upon one another concentrically, giving rise to laminated masses somewhat resembling concretions and often distinguished from them with difficulty.

Much the most important development of the Cœlenterates was the rise of the graptolites, whose important function in correlation has already been discussed, and which will be further considered presently. Some of the typical forms are illustrated in Fig. 167.

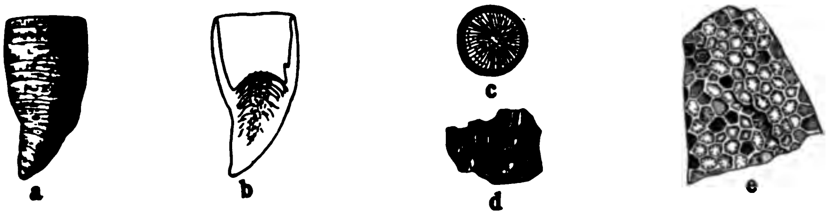
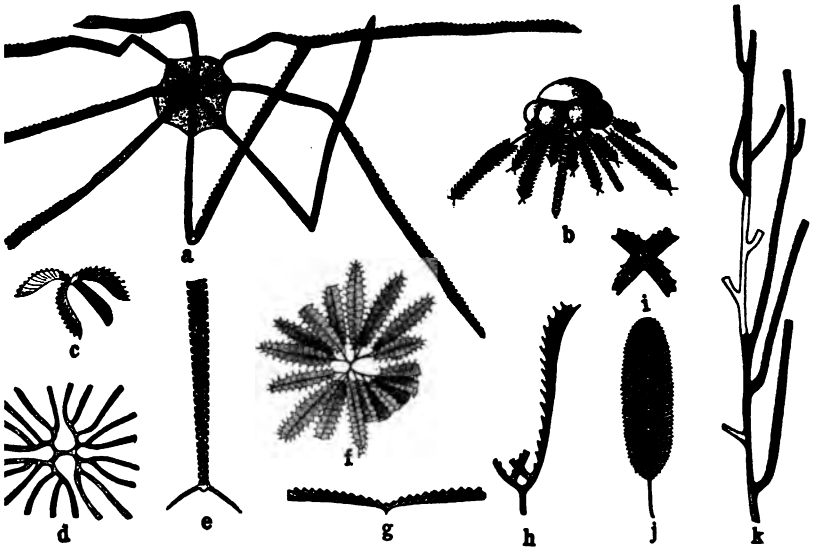


FIG. 166.—*Ordovician Corals.* *a–c*, *Streptelasma corniculum* Hall, exterior view with longitudinal and transverse sections, showing internal characters. *d*, *e*, *Columnaria alveolata* Goldf. While both simple and compound corals were present in the Ordovician faunas, they rarely formed great reef-like masses, as in later periods.

Other forms.—Sponges were present and sometimes attained notable sizes, but they played only a small part in the fauna (Fig. 168). Annelids were represented, but less abundantly than in the Cambrian, perhaps because the prevalently muddy and calcareous sea-bottom of the Ordovician was less congenial to them than the Cambrian sands. They are represented not only by burrows, but by teeth (Fig. 169). Protozoans were probably present, but their minute and fragile shells can be recognized only with some uncertainty.

Implied life.—If here, as in the discussion of the Cambrian life, we inquire what forms other than those fossilized are necessary to round out a rational assemblage of life, a briefer answer may be given, for the Ordovician fauna was a nearer approach to a theoretically complete assemblage. A vast supply of unrecorded vegetation must be postulated as a food-supply, as before, and to provide a complete chain of food-supplies for each one of the whole series of organisms that preyed upon another in succession, from the plants up to the master forms o predaceous animals, there must doubtless have been many inter diate species that are not now known. The defensive investitures o lower forms, not fully accounted for by the known Cambrian specie now much more nearly explained by the prevalence of the cephalc ds and the presence of fishes; and the armorings of these dominan ms may have been defensive against their own kind. The fact tha rly all vegetal and animal tissue perished, and is not even repre



. 167.—*Ordovician Graptolites.* *a*, *Dichograptus octobrachiatus* (Hall); *b*. *Dip graptus pristis* (Hall) (restored by Ruedemann); *c*, *Tetragraptus bigsbyi* (Hal (*d*), *Dichograptus logani* (Hall); *e*, *Climacograptus bicornis* (Hall); *f*, *Reteograp eucharis* Hall; *g*, *Didymograptus nitidus* (Hall); *h*, *Tetragraptus fruticosus* (Hal *i*, *Phyllograptus ilicifolius* Hall; *j*, *Phyllograptus typus* Hall; *k*, *Holograptus ri ardsoni* (Hall).

ted by organic deposits save in exceptional cases, probably signifi at bacteria and allied forms that are concerned in the decompositi tissue were present in abundance. What are interpreted as fos cteria are found a little later in some of the earliest vegetal tissu at are well preserved, and what seem to be the characteristic effe bacteria on the tissues are also then recognized. This gives supp the view that the very general destruction of the tissues of the high dovician animals and plants was the work of such destructive mic ganisms. The paucity of the fossil record was therefore perhaps much or more due to these as to unfavorable physical conditions. Rather paradoxically it may perhaps be said that the very scantiness of life relics is due to the abundance of certain forms of life.

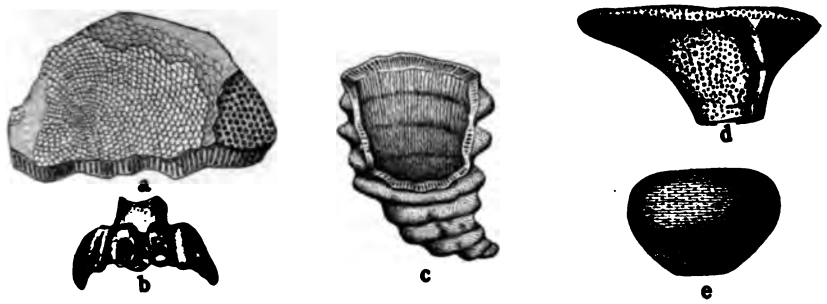


FIG. 168.—*Ordovician Sponges.* *a*, *Receptaculites occidentalis* Salter; *b*, *Brachiospongia digitata* Beecher; *c*, *Archæocyathus minganensis* Billings; *d*, *Strotospongia maculosa* U. and E.; *e*, *Ischadites*, species undetermined. The *Receptaculites* and *Ischadites* have sometimes been regarded as giant foraminifers.

Ecological, social, and mental development.—It is not necessary to more than briefly recur to the ecological, social, and psychological considerations to which attention was called in the discussion of the Cambrian life, for they remain essentially the same, save that the ampler development and better preservation of the Ordovician fauna give greater definiteness to the problems and supply more data for their elucidation. It seems clear that the adaptation of the various forms of life to one another and to their physical environment had reached a higher stage of adjustment, indeed a degree of adjustment not very greatly inferior to that which now prevails among the corresponding

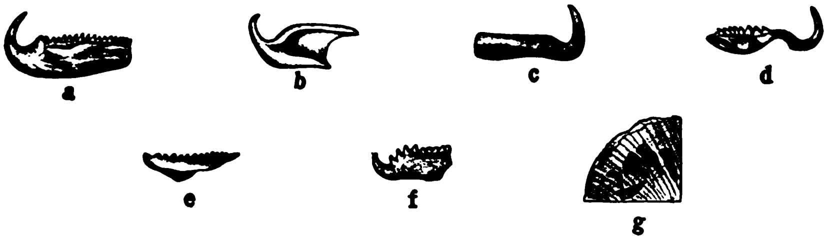


FIG. 169.—*Ordovician Annelids.* *a*, *Arabellites cornutus* Hinde; *b*, *Glycerites sulcatus* Hinde; *c*, *Eunicites gracilis* Hinde; *d*, *Arabellites ovalis* Hinde; *e*, *Eunicites varians* (Grinnell); *f*, *Oenonites rostratus* Hinde; *g*, *Ortonia minor* Nicholson. Figures *a*, *b*, *c*, *d*, *e*, and *f* are highly magnified illustrations of the jaws of annelids. Figure *g* is an example of the calcareous tubes secreted by some annelids attached to other shells.

ders; and it is not improbable that the mental development al
proached somewhat nearly to that now possessed by corresponding
w types. Higher biological types within the same orders have ce
inly been developed since in many cases, and probably higher ment
nctions; but some of the Ordovician forms have since suffered bi
gical degeneration, and probably also mental degeneration. T
rdovician ancestor of the barnacle, a free-moving active form, w
ubtless superior to his sessile descendant of ill-repute. The su
tal of ecological adaptation, and of social and mental developme
wever, seems to have advanced with each era, though perhaps n
ways with each of the briefer stages.

The Succession of Faunas.

1. **The Fauna of the Calciferous.**—The Calciferous in its typical devel
ent, in New York and the interior, is usually very poor in fossils, and these
orly preserved. It is therefore difficult to find species that have a wide g
aphical range and yet are known to be so closely confined to this horizon
be characteristic of it. Of the species so regarded the most widely av
le is the gastropod, *Ophileta complanata* (Fig. 161, *k* and *l*).

Certain genera are usually present, however, in most faunas of this age, am
ich may be mentioned *Tryblidium* and *Eccyliomphalus* among the gastropo
mtrophia and *Camarella* among the brachiopods, *Orthoceras* and other gen
ong the cephalopods, and *Bathyurus* among the trilobites.

Doubtless many more or less imperfectly known species are really charac
ic of the formation, but are not sufficiently prevalent and well preserved
ve good evidence of it. Of connecting species, and hence not characteri
es, there is a small list of which some range below and some above. For
eater part, the fossils are so sparse and so imperfect that their range and
ficance is not determinable. In the Champlain and the lower St. Lawre
lleys where the formation is greatly thickened and appears to be less shar
stinguished from the formations below and above, a more ample fauna is fou
d in it more species that range into the overlying and underlying formati
irty-five genera and one hundred species are announced from the vicinit
ke Champlain, but the ranges of these have not yet been determined.[1]

In the shales of the Lévis formation in the lower St. Lawrence Valley m
aptolites are found. These belong to the *Phyllograptus* zone, which embr
e subzones of *Tetragraptus* and of *Didymograptus bifidus*.[2] They repre
horizon corresponding to the Arenig of Great Britain. The *Tetragraptu*

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[1] Brainard and Seeley, Bull. Geol. Soc. Am., Vol. I, 1890, pp. 501, 513; Vol.
91, pp. 293, 300; Whitfield, ib., Vol. I, pp. 514, 515.

[2] Lapworth, Trans. Roy. Soc. Can., 1886; also Ann. Rep. Geol. Surv. Can., 1877
rt II, p. 45K; also Ann. Nat. Hist., 5th Series, Vol. VI, 1880, p. 197.

regarded as marking the lowest horizon of the Ordovician. Of the graptolites illustrated in Fig. 157 those designated *a*, *c*, *d*, *g*, *i*, *j*, *k*, and *l* belong to the *Phyllograptus* zone, the most of them to the lower subzone. If this horizon could be traced to the interior, the lower limit of the Ordovician would there be fixed on excellent paleontological grounds and on an intercontinental basis. Unfortunately, the correlation of the graptolite-bearing Lévis beds of the St. Lawrence basin with beds in the interior is attended by grave difficulties on account of the contortion and faulting the Lévis has suffered, and the absence of graptolites from typical beds of the interior. The correlation has therefore been the subject of much difference of opinion. There appears to be a series of beds of great thickness below the Lévis that is referable to the Calciferous, which implies that the graptolite beds are not as old as the oldest Calciferous, but they have nevertheless usually been referred to the Calciferous, and the latter placed in the Ordovician. If, however, it shall ultimately prove that the *Phyllograptus* beds lie above the unconformity at the summit of the Calciferous in New York and its equivalent in the interior, or shall be found to represent that unconformity itself, the paleontological and the physical planes of division will be brought into harmony, and the original Calciferous will be referable to the Cambrian. There are graptolite beds in Arkansas and Nevada that belong to the same general horizon as those of the Lévis, though they present peculiarities, but they cannot be closely correlated stratigraphically with the original or typical Calciferous.

2. **The Chazy Fauna.**—The recorded fauna of the Chazy is much more ample than that of the Calciferous, and is closely related to the Mid-Ordovician fauna, of which it was an immediate forerunner in a closer and more obvious sense than was the Calciferous fauna a forerunner of the Chazy. *Maclurea magna* is regarded as the most characteristic fossil, and next to it perhaps is *Camarotœchia plena*. Other fossils regarded as essentially characteristic are the brachiopods, *Hebertella imperator*, *H. costatis*, *Dinorthis platys*, *Lingula lyelli*, *L. huronensis*, and *Rhynchonella orientalis;* the gastropods, *Pleurotomaria calyx*, *Metoptoma dubia;* the pelecypod, *Modiolopsis parviuscula;* the corals, *Columnaria incerta*, *C. parva*, *Streptelasma expansum;* the cystoids, *Malocystis murchisonia*, *Palæocystis tenuiradiatus;* the trilobites, *Bathyurus angelini*, *Amphion canadense*, *Amphyx halli*, *Harpes antiquatus*, *Illænus arcturus*, and the ostracode. *Leperditia canadensis.* Some species found in the Chazy range upwards into the Middle Ordovician and bind the Chazy fauna to it, and a few range down into the Calciferous. The Chazy fauna is fairly well characterized in the Champlain and St. Lawrence Valleys, but in the interior and west it is not distinctly differentiated, but appears to be lost in a larger assemblage of forms. It is hence inferred that it came in from the east and mingled with resident forms. Perhaps it developed in part in the St. Lawrence embayment before it was united with the interior sea after the stage of separation implied by the inconformity mentioned above. It is there that it has its closest relations to the Calciferous fauna, or at least to the eastern phase of that fauna.

3. **The Mid-Ordovician Fauna.**—While the special group of forms that con-

tuted the Chazy fauna probably came into the great interior sea of Mid-Or
cian times from the eastward, and thus contributed to its fauna by immig
on, there is reason to think that other species had developed indigenously
e southern and western portions of that sea, and that still others came in fr
e other coast regions with which connections were had. In the Great Ba
pper Cambrian species are found to mingle with Ordovician species thro
notable vertical range. This implies that the transition was indigenous th
d that the sea was persistent. It seems also to imply either that the C
ian fauna was prolonged there or that some species that are best known la
the Mississippi basin and the Atlantic province came in there relatively ea
r example, *Orthis testudinaria*, which abounds in the Middle and Upper Or
cian of the Mississippi and Atlantic provinces and occurs in the Lland
id-Ordovician of Great Britain), is found associated with *Dikellocepha*
d *Ptychoparia* (Cambrian genera) in Nevada.[1] In Tennessee and Kentu
ere was a long period preceding the climax of the Mid-Ordovician fauna, du
ich there flourished an abundant fauna made up of species common in
terior and western regions, but only sparsely represented in the Chazy hori
the Champlain-St. Lawrence embayment. These and similar facts warr
e view, which is to be held merely as tentative in the present state of inve
tion, that the Mid-Ordovician fauna of the interior is to be regarded, not
e simple successor of the Chazy fauna, or of any single earlier fauna, but
e common product of faunal elements derived from the coast regions on
rious sides of the continent, commingled with resident forms that had evol
om the Cambrian fauna in the interior sea. This interior sea was m
ntracted on the north and east at the close of the Calciferous stage, but d
t appear to have been wholly withdrawn. The contraction doubtless led
ovincial evolution in the residual, more or less dissevered portions; but w
e readvance of the sea that took place at the beginning of the Mid-Ordovici
e subfaunas so developed, commingled, and a common evolution took pla
is Mid-Ordovician fauna is therefore only locally and partially to be regar
the successor of the distinctive Chazy fauna or of any other invading fau

The Mid-Ordovician fauna was very prolific, and it is made to seem sin
rly so by contrast with the scantiness of the Calciferous fauna. It is not
characterized by a few species, as in the preceding cases, but rather by
eatness, variety, and cosmopolitan character of its assemblage of thousa
species from various outside and inside sources of derivation. Its nat
ay be gathered by reviewing the forms illustrated in Figs. 157-169 inclusi
nitting the graptolites, a portion of the bryozoans, and a few other spe
ecially mentioned under the other Ordovician faunas. The general aspect
ese groups, when commingled, gives the general aspect of the Mid-Ordovic
una. Locally there were modifications, such as gave rise to the Birdse
lack River, Galena, and other special subfaunas of more or less local imp
nce. There were also stages of progress common to wide areas that were mar

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[1] Walcott, Pal. Eureka Dist. Mon., VIII, U. S. Geol. Surv., 1884, p. 1.

by the incoming or outgoing of particular species or groups of species. These represent the evolution of the fauna in a broader sense. For the greater part these stages are yet to be worked out into precision and detail, though clearly recognizable in general terms.

4. **The Upper Ordovician Fauna.**—The closing fauna of the Ordovician in North America retained most of the characteristics of the Middle fauna, from which it was directly descended without radical modification due to interruption of the controlling conditions. The chief change in the physical influences lay in an increased prevalence of silt sedimentation and in the shallowing and final withdrawal of the great epicontinental seas. With the development of the silt sedimentation there came a very notable increase, relatively at least, in the bryozoans (Fig. 161, *a* and *b*) and of the graptolites (Fig. 167, *b*, *e*, and *f*). The pelecypods were favored by the mud bottoms and became prolific. More than eighty species have been identified in a limited district in southern Ohio and Indiana.[1] There was a relative decline in the number of gastropods, cephalopods, and trilobites, and, in general, the fauna was perhaps less prolific; at least this appears to be so from the larger proportion of matter of inorganic derivation to that of organic derivation.

The closing phase of the Upper Ordovician was the withdrawal of the fauna of the interior as a necessary attendant of the withdrawal of the interior sea. The succeeding fauna contained an almost entirely new assemblage of species, though many of the genera remained the same. In the St. Lawrence embayment, the Ordovician fauna lingered longer and was gradually changed into or replaced by the Silurian fauna. Probably the same was true in other embayments on the border of the continent and along its coast generally.

The Ordovician Fauna of Other Continents.

Much the same general lines of progress were followed on other continents, and the general aspects of the successive subfaunas were much like those of the American continent. Usually the genera were the same, but the species as a rule were different, though they often bore a close resemblance to the American species. In northwestern Europe, with which the means of migratory communication seem to have been the freest, not a few common American species flourished, such as *Dalmanella testudinaria*, *Platystrophia biforata*, *Dinorthis porcata*, *Leptæna rhomboidalis*, *Plectambonites sericeus*, *Halycites catenulatus*, and *Trinucleus concentricus*. In Asia, so far as present limited information goes, the species were nearly all different, the wide-ranging graptolites excepted, though *Halycites catenulatus* and *Plectambonites sericeus* are found in China. The stages of progress in the shallow-water faunas of the Old and New World are to be regarded rather as parallel than as identical. The evolution in Europe, where alone details have been well worked out, was usually on less broad lines than that of the American interior, for the obvious reason that the epicontinental seas were more limited and more interrupted by barriers.

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[1] Ulrich, Geol. Surv. Ohio, Vol. VII, 1893, pp. 626–693.

CHAPTER VII.

THE SILURIAN (UPPER SILURIAN)[1] PERIOD.

FORMATIONS AND PHYSICAL HISTORY.

THE physical changes which brought the Ordovician period to lose marked also the inauguration of the Silurian. These chang will be recalled, involved (1) movements which affected small ar ntensely (orogenic), and (2) movements which affected broad ar ightly (epeirogenic). From the standpoint of continental histo he gentler movements were the more significant, since they affec arger areas. It is not to be understood that these changes, whet rogenic or epeirogenic, were sudden or violent. Rather is it to upposed that the formation of mountains and the emergence of la arts of the North American continent from the epicontinental which had covered it during the Ordovician period, occupied a c iderable interval of time, including the later part of the Ordovic nd the early part of the Silurian. After these changes had tal lace, the area of land shown in Fig. 129 was greatly enlarged, ndeed more considerable than at any previous time since the e ambrian (see Fig. 90, p. 220). With the increase in the area of l ame lengthened streams, and presumably increased erosion, tho he land areas were probably not of sufficient extent to give rise treams equal in size to the largest of those of the present time.

Could the relations of land and water at the beginning of the Silu e accurately defined, their statement would at the same time de n a general way the areas where the earliest sedimentation took pl ot only this, but it would also define in a general way the areas wh edimentation was rapid and where slow, for then, as always, s reas must have stood in more or less definite relation to the sh f the oceans. It is safe to assume that at the opening of the Silu

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[1] When the name *Lower Silurian* is used instead of Ordovician, *Upper Silu* used in place of *Silurian,* as that term is here used.

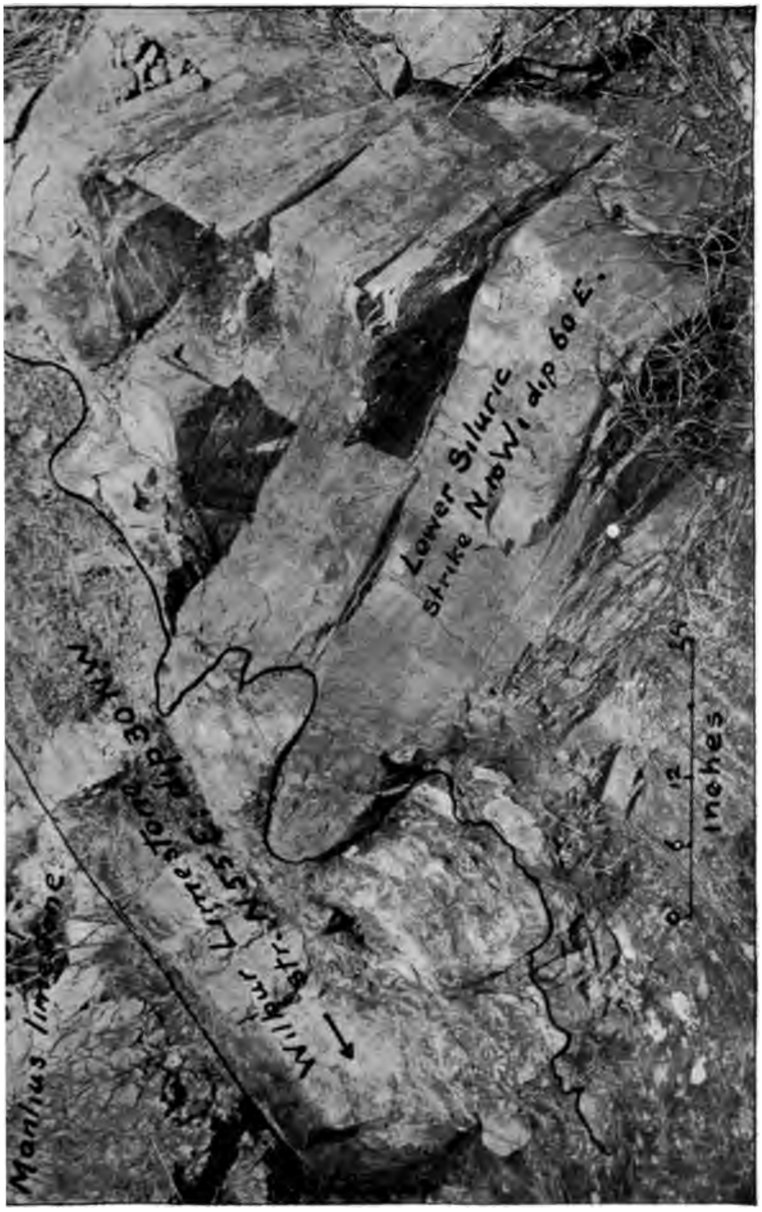

FIG. 170.—Unconformity between the Ordovician and Silurian. South end of Vlightburg, Rondout, N. Y. (Photo by Van Ingen, N. Y. State Geol. Surv.)

period beds of clastic sediments were accumulating about the in diate borders of the lands, and as far out as waves and currents able to transport abundant detritus from the land, and that elsew sediments of organic origin were relatively more important. Th sedimentation was interrupted in the regions which emerged the sea during the transition from the Ordovician period to the Silu it must be assumed that such interruption was not universal, and where it did not take place, the Silurian strata are conformabl the Ordovician. It may be assumed further that at each stag the Silurian period, the exposed portions of each older formation contributing to the system then in process of formation. The of sedimentation at any particular stage of the Silurian cannot be determined by the geography of that stage; rather is the geogr of the successive stages of the period determinable in some me by the successive areas of sedimentation.

SUBDIVISIONS OF THE SILURIAN SYSTEM.

The Silurian system of rocks is divided into a number of forma or series of formations. The principal subdivisions which have commonly recognized in America are given below.

The Helderberg series, though sometimes classed as Siluria here classed with the next later (Devonian) system.

[(Lower) Helderberg?]
5. Salina
4. Niagara
3. Clinton
2. Medina
1. Oneida

In place of the above classification, the following has recently proposed for New York:[1]

Ontaric[2] or Siluric	Cayugan Neontaric	Manlius limestone
		Rondout waterlime
		Cobleskill limestone
		Salina beds
	Niagaran (Mesontaric)	Guelph dolomite
		Lockport limestone
		Rochester shale
		Clinton beds
	Oswegan (Paleontaric	Medina sandstone
		Oneida conglomerate
		Shawangunk grit

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[1] Clark and Schuchert, Science, Vol. X, 1898, p. 876, and Am. Geol., Vol. 1900. Slightly modified by Hartnagel, N. Y. State Mus. Bull. 69, 1903, p. 116

[2] The term Ontaric was first used in this sense by Emmons (Agr. of N. Y.,

The principal subdivisions of this classification, modified as below, will be followed:

Silurian
- Cayugan
  (Neo- or Upper Silurian)
- Niagaran
  (Meso- or Middle Silurian)
- Oswegan
  (Paleo- or Lower Silurian)

In this case there is some objection to the use of the terms Lower, Middle, and Upper Silurian, since Lower Silurian has been used as a synonym for Ordovician, and Upper Silurian for Silurian, as that term is here employed. The subdivisions in the third column of the above table (p. 370) are to be accepted for New York, but are not all applicable to other regions.

A brief sketch of the nature and distribution of these principal subdivisions of the system will throw much light on the history of the continent during the Silurian period.

THE OSWEGAN SERIES.

The Oneida formation.—The lowest and therefore the oldest formation of the Silurian system is the Oneida. It appears at the surface at various points in the Appalachian belt south of the Shawangunk (pronounced Shongum) mountains (N. Y.), though different names are applied to it in different regions, and it is not everywhere separated from the succeeding Medina. To the south, the formation seems to be restricted to the western part of the Appalachian system. Since the formation appears to rest conformably on the Ordovician, it is inferred that sedimentation was not interrupted, in the region where the formation occurs, during the transition from the Ordovician period to the Silurian.

The Oneida formation of the Appalachian belt is not known to extend west of the mountains, and it is now believed to have been accumulated in a narrow basin within the present Appalachian belt, completely shut off from the great interior (see Fig. 182, p. 390). It is not known whether the area where it occurs was submerged, or whether it was the site of subaërial deposition. The fact that the formation is without fossils lends color to the view that its sediments

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pp. 141–152), in 1846. It had been used earlier in a more restricted sense (Mather, Nat. Hist. of N. Y., Pt. IV, pp. 353–4.

were deposited on land, or in an enclosed body of water not connected with the sea. On the other hand, the materials of parts of the formation are so perfectly assorted, and the p so thoroughly rounded, as to suggest wave rather than stream If the formation is of marine origin, the coarseness of the sedi may help to explain the absence of fossils, for where coarse sedi are gathering, shells are more likely to be destroyed, and sc they are buried, they are likely to be dissolved at a later time b of the free circulation of water through the porous beds.

South of Lake Ontario there are beds which have been clas Oneida. They are fossiliferous and clearly associated with the M formation of the region. They are believed to have been de in waters which were separated from the Appalachian basin a referred to. The term Shawangunk, applied to the eastern b not applied to the more westerly ones.

The Shawangunk (or eastern Oneida) formation is about 5((maximum) thick in New York, and 800 feet in Pennsylvania. in its constitution and structure it bears the marks of shallow (or subaërial) deposit, being chiefly of sandstone and conglo often cross-bedded and ripple-marked. The materials of the tion seem to have been derived from older lands to the east. are essentially quartzose, and represent the products of rock rather than of rock breaking. The abundance of quartz pebbl gests that the metamorphic rocks of Appalachia had long been going decay before the advent of the Oneida epoch, but that t surface had stood so low as not to allow of the removal of the products of decomposition. If, following such a period, th were elevated, rejuvenating the streams, such material as t which the Oneida formation is composed would have been down to the sea or to low-lying lands. The character of the vician beds (limestone and fine sediments) in the region of the formation is consistent with the sequence of events here sug

The Oneida formation, composed at the outset of durable ma has been so thoroughly indurated by compression and cementa to become exceedingly obdurate. The outcropping edges of it beds (Fig. 171) constitute the crest of the Kittatinny range i York, New Jersey, and Pennsylvania (Fig. 172). Not only d Oneida conglomerate constitute the crest of this range, but th owes its existence to the obduracy of this rock, which successfully withstood erosion while the less resistant formations to the east and west were carried away. The same formation (the Green Pond Mountain conglomerate) appears also in the Green Pond mountain of New rsey, and in its northward continuation in New York. The outcrop the Oneida is also conspicuous farther south, and for the same reason.

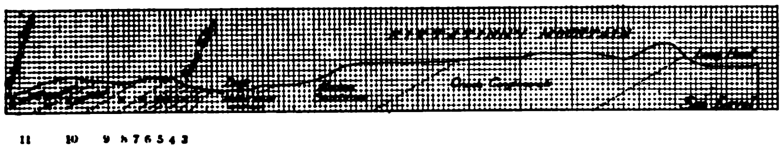

FIG. 171.—A section across the Kittatinny Mountain in northwestern New Jersey. Length of the section, about five miles; vertical scale, nearly twice the horizontal; angle of dip, approximately doubled. 3 = Poxino Island shale; 4 = Bossardville limestone; 5 = Decker Ferry beds; 6 = Manlius limestone and Rondout limestone; 7 = Coeyman limestone; 8 = Becraft limestone, New Scotland beds, and Stormville sandstone

G. 172.—The Delaware Water Gap. The crest of the mountain range seen in the background is the crest of the Kittatinny range made by the resistant Oneida conglomerate.

The Medina formation.—The Medina formation, consisting of ndstone and shale (including the Longwood shale of the Green Pond ountain region), overlies the Oneida. Its materials, like those of the Oneida, appear to have been accumulated in shallow wate possibly on land. This is shown by the cross-bedding, the ri marks, etc., which affect the surfaces of its layers. In view of t facts, and in view of the physical similarity of the two formations of the conformity of the younger on the older, it is inferred that deposits of the Medina stage followed those of the Oneida wit interruption where both formations are present. Like the ea Oneida, the eastern (Appalachian) Medina seems to have been depo in a basin which had no connection with the interior. Beds class Medina are also found south of Lake Ontario, where they overli Oneida of the same region. They appear at the surface as far we eastern Ohio and Ontario, where they thin out and disappear. of this longitude, the formation has not been identified.

The Oneida and Medina formations south of Lake Ontario co marine fossils, showing that an interior sea existed in this regi early Silurian time. The distribution of the two formations indi a more extended sea in the later than in the earlier epoch, and p to a subsidence of the eastern interior during the early part o Silurian period. By the close of the Medina epoch, as the distrib of the Medina formation shows, the area of deposition had been exte at least as far west as Ohio (the Cincinnati arch).

The Medina formation, which has but a narrow outcrop in nor New York, is probably continuous beneath younger strata over of the state south of Lake Ontario and the Mohawk valley, and w the Appalachian basin, and farther south over considerable areas of the Appalachians. Nothing is known of the sediments which have been accumulating along the eastern border of Appalachia of those about the other land areas of the time. Though the O and Medina formations are unknown both in the interior west of and in the western part of the continent, it is possible that s which are their time-equivalents exist in some parts of this vast ritory. If they anywhere appear at the surface, they have not identified.

In Pennsylvania, the eastern (Appalachian) Medina formatio a maximum thickness of something like 1800 feet. This, it is remembered, was near a great land-area to the east whence the ments were doubtless derived. West of the Appalachian belt formation is much thinner, having in Ontario a thickness of 300 t feet. The material for that part of the formation which lies in northern New York and Ontario probably came from the north. The lesser thickness of the formation in this region, as compared with that of Pennsylvania, suggests either that the rate of accumulation was slower, or that the formation in Ontario does not represent the full series of beds belonging to the epoch.

THE NIAGARAN SERIES.

The Clinton formation.—The formation next younger than the Medina is known as the Clinton formation. Where the younger formation overlies the older they are generally conformable, but the distribution of the two is so different as to indicate that geographic changes of importance were in progress as the Silurian period advanced. The Clinton formation extends farther east and farther west than the Medina, indicating an expansion of the eastern interior sea in both directions. To the westward the Clinton extends to Lake Huron and Indiana, and perhaps to northern Illinois and eastern Wisconsin, and even to northeastern Missouri. If it extends so far west, it is made up of beds which have usually been classed as Niagara. It is not known whether the Cincinnati arch was submerged at this time, or whether it was an island in the Clinton sea. Southern Indiana and southern Illinois seem not to have been submerged. The Clinton formation also occurs in the Appalachian mountains as far south as Alabama and Georgia. It seems probable from the evidence now in hand that the elongate basin in which the sediments of the Clinton formation of this mountain belt accumulated was separated from the interior sea, or at least not freely connected with it. This inference is based chiefly on the dissimilarity of the faunas of the beds classed as Clinton in the Appalachian belt and in the interior.

Sedimentary beds which are believed to belong to the Clinton epoch have been recognized in Nova Scotia (a part of the Anticosti series) and at a few other places northeast of the United States. In this region marine sedimentation was probably continuous through the Ordovician and Silurian periods, and the correlation of the strata with those of the interior is attended with difficulty and uncertainty. The materials for these beds, so far as clastic, were probably derived from land to the west.

The variations in the character of the Clinton beds in diffe localities are not without significance. In the Appalachian mounta the Clinton sediments were largely sand and mud, now in the condi of sandstone and shale. In western New York and beyond, muc the formation is limestone, showing that the seas of that region relatively clear, and that organic sediments predominated over cla Bryozoan reefs, resembling coral reefs, occur in this formation in ern New York.[1] The limestone does not mean that the water was ne sarily deep, but rather that the water in which it was deposited wa nearly free from clastic sediments that the shells, etc., constituted principal part of the deposit made. Shell-bearing life may be jus abundant where sand and mud are accumulating as elsewhere, bu this case the product is not limestone, but sandstone, shale, etc., taining shells.

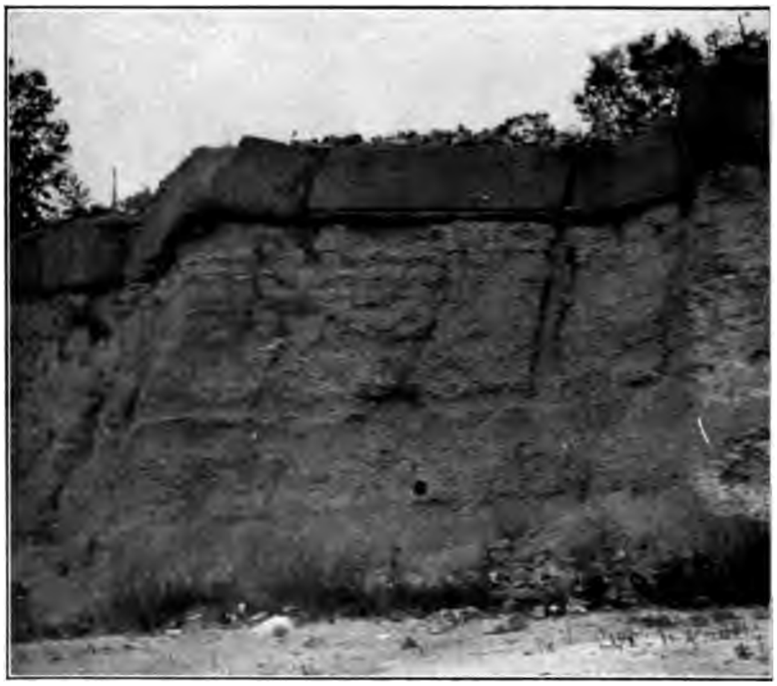

FIG. 173.—The Clinton formation with **Niagara overlying. Howe's Cave,** (Darton, U. S. Geol. Surv.)

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[1] Sarle, Am. Geol., Vol. 28, p. 282.

One of the notable features of the Clinton formation is the presence in it at many points of iron ore. Chemically, the ore is generally in the form of hematite. Physically, it is often made up of small concretions which so resemble flaxseed in size and shape as to have suggested the name "flaxseed" ore. Locally it is known also as "fossil" ore from the abundance of fossils which it contains. The ore is known at many points between New York and Alabama,[1] as far west as Wisconsin [2] (where it is the only representative of the formation which has been commonly recognized), and as far northeast as Nova Scotia. The ore beds are interstratified with other beds of the formation, and are usually believed to have been accumulated by chemical precipitation in marshy flats. Since the iron compounds in solution in the water were derived from rock formations in process of decay, the extraction of these compounds being itself one of the elements of decay, the iron ore, as well as the other beds of sedimentary rock, had its origin in the decay of the older formations. The iron was probably deposited in the form of limonite ($2Fe_2O_3 . 3H_2O$) or of iron carbonate ($FeCO_3$), and subsequently changed into its present form (Fe_2O_3). This is the fourth series in America which contains a large amount of iron ore, the first, second, and third being in the Archeozoic, the Huronian, and Animikean respectively. Like the Clinton iron ore of Wisconsin, the manganese ore deposits [3] of Arkansas lie at the base of the Silurian system in that region, and the two classes of ore may have had a somewhat similar origin.

The Clinton formation has a thickness of 900 or 1000 feet in Pennylvania, of 800 in Virginia, and of 200 or 300 feet in eastern Tennessee nd Kentucky. In the eastern interior, the formation is much thinner.

Like the Oneida and Medina formations which preceded, the Clinon beds have not been identified in the western half of the continent.

The Niagara formation.—The Clinton formation of the interior was succeeded by the Niagara (Rochester shale, Lockport limestone, nd Guelph dolomite of New York; see p. 370), which extends somewhat farther west than any of the preceding Silurian formations, showng that the submergence of the earlier epochs still continued in the upper Mississippi basin. The Niagara formation covers not only nuch of New York, Ontario, and Ohio, but also all or nearly all outhern peninsula of Michigan, much of Indiana and Illinois, parts of Wisconsin and Iowa. North of Missouri, it is not known occur far west of the Mississippi. It was formerly supposed to present in the Black Hills of South Dakota, but this correlation se o be doubtful.[1] It may yet be found where it has not been rec nized, or where its identification has not been placed beyond quest The formation probably never extended east over the Cincinnati r the similar Nashville dome to the south, though it extended between them. To the westward it extended beyond the Mississ nto eastern Missouri, Arkansas, and perhaps even to the Arbu nountains in Indian Territory. It was in this epoch, as the relati of the next succeeding formation show, that the submergence which been in progress since the beginning of the Silurian period, reac ts maximum in the upper Mississippi basin. In the southeast part of the same basin, the sea of the Niagara epoch was prob more restricted than that of an earlier time.

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[1] See geological reports of the several States; also Jour. Geol., Vol. IX, p. 412.

[2] Geol. of Wisconsin, Vol. I, 1881.

[3] Penrose, Geol. Surv. of Arkansas, Vol. I of the Ann. Rept. for 1890.

The southern border of the interior sea is not known, but it app not to have been connected with the ocean in this direction. and barrier which limited it on the south appears to have been the position of the Gulf States. These general facts are expre on the map, Fig. 174.

Beds of sedimentary rock contemporaneous with the Niagara the interior may exist in the northern part of the Appalachian but their faunas are so unlike those of the Niagara of the Mississ basin as to indicate the continued separation of the Appalachian b from the interior. Because of these conditions, exact correlat between the second group of the Middle Silurian series (p. 371) of interior, and the corresponding beds of the Appalachian trough, h not been made.[2] The upper part of the Niagaran series (above Clinton) is believed to be absent from the southern Appalachians, region where most of the preceding formations of this period an the Ordovician are well represented. Their absence from this reg appears to mean that the shore of the interior sea was tempora shifted to the west, either because of crustal movements which ca

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[1] Beecher, Am. Geol., Vol. XVIII, p. 31.

[2] Weller, Rept. on the Paleozoic Paleontology of New Jersey, Geol. Surv of N 1903.

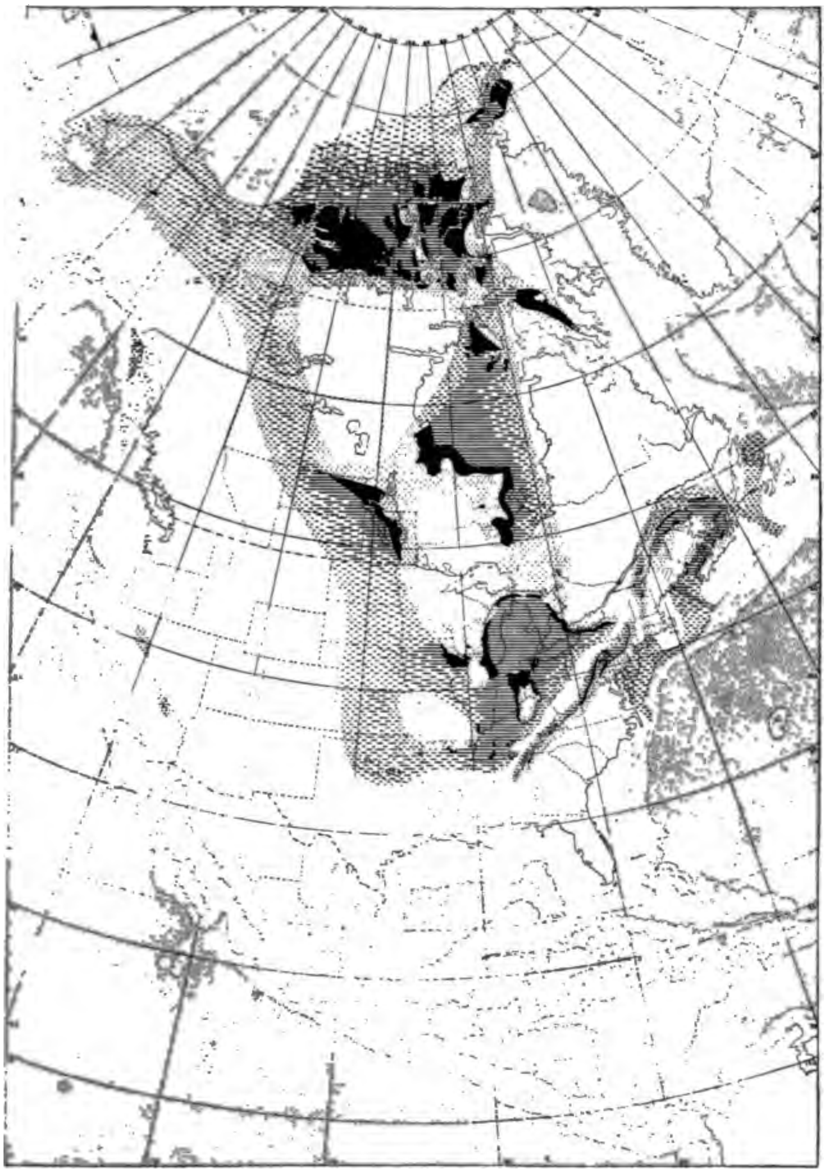


FIG. 174.—Map showing the outcrops of the Niagara formation, and at the same time the general relations of land and water during the Niagara epoch. The various sorts of shading on the map correspond with those on earlier maps (see p. 220).

land to emerge, or because the sea-bottom had been converte land by aggradation.

ι significant feature of the distribution of the Niagara formatioı e associated with its distribution in the interior of the continen s great development in high latitudes. It occurs in Manitoba from here probably extends down into Minnesota. While thi of Niagara is not known to be connected with that of Iowa an ois, such connection is probable, being now obscured by the heav r of drift which covers most of Minnesota. The Niagara forma is also present west of Hudson Bay, and over numerous larg small areas on the continent and on islands between the paralle 0° and 76°. It is also present in Grinnell Land and Greenland i ude 80°.

'he isolated areas of the Niagara formation in these norther ons appear to be remnants of a once continuous body. Thi ence is rendered probable by the similarity of the fossils througl

175.—Contact of the Niagara limestone and the Maquoketa (Hudson Riv ιale) in northeastern Iowa. The view illustrates the effect of inequalities ırdness on topography. The cultivated surface with the gentle slope is unde in by Hudson River shale; the wooded slopes above are the escarpment iagara limestone. (Calvin, Iowa Geol. Surv.)

the northern area. From the same line of evidence, it is inferre there was shallow water connection between the Mississippi basi northern Europe by way of the arctic islands, a connection whic ıitted the intermigration of the shallow-water animals of the tw ons.

Between the northern areas of exposed Niagaran, older formatior ι which the Niagara has been removed are exposed. In the Unite es, on the other hand, the more or less widely separated area of exposed Niagara are separated because the formation is concealed at intervening points by younger beds.

The distribution of the Niagara formation in the interior, taken with the distribution of the earlier Silurian formations, would lead to the conclusion that the Niagara should rest on the Hudson River shales unconformably over a large area in the Mississippi basin. Such is doubtless the fact, yet the degree of unconformity is so slight as not to be readily detected. This might mean either (1) that the older formation was elevated so little at the close of the Ordovician, and stood so low during the Oneida, Medina, and Clinton epochs, as to have suffered little erosion, or (2) that it was almost perfectly base-leveled before the Niagara epoch. In both cases it would be necessary to suppose that the strata were little deformed, since the bedding of the two formations is essentially harmonious. Between these two alternatives, the former is perhaps the more probable.

In New York the beds which were formerly grouped under the name Niagara, and now under the series name, Niagaran, consist of shale (Rochester, p. 370) below, and limestone (Lockport and Guelph) above. It is the more resistant beds of the latter overlying the more yielding layers of the former (Fig. 176) which have given rise to the Falls of the Niagara, the locality whence the formation takes its name, and determined the position of the escarpment between Lake Ontario and Lake Erie (Fig. 177) from which the Falls (at *F*) has retreated. The same limestone has determined other falls, such as the uppermost falls of the Genesee river, shown in Fig. 178. West of New York the formation is mainly limestone. Except the Trenton, it is more wide-spread than any preceding formation of limestone, and tells of an expanse of clear water covering much of the great Mississippi basin.

The Niagara formation is the oldest in which well-developed coral reefs have been identified. While coral-secreting polyps had lived before, as shown by their abundant fossils in older formations, and while their secretions had helped to make the Trenton and other limestones, the reef-building species seem to have first become abundant in mid-Silurian time. The reefs are known in eastern Wisconsin and at other points farther south and east. Coral reefs and the adjacent deposits illustrate as clearly as anything else among the ancient formations the methods by which limestone deposits were formed. The reefs themselves are composed of the commingled relics of the life that

ew upon them. Great masses of coral may sometimes be seen stan
g erect in the rock precisely as they grew, having entirely escap

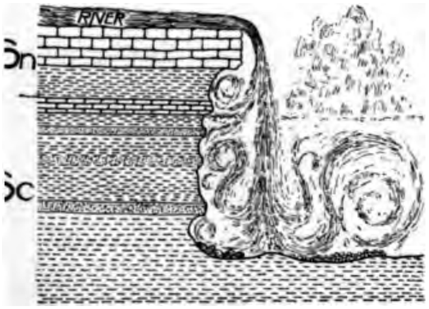


Fig. 176.

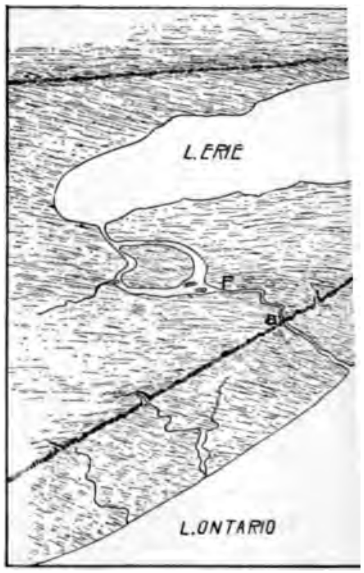
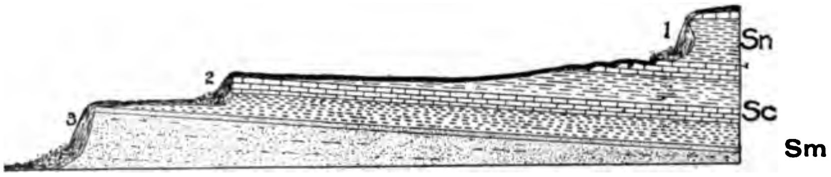


Fig. 177.

ig. 176.—Diagrammatic section showing the relations of rock formations Niagara Falls. (Gilbert.)
ig. 177.—The Niagara escarpment. (Gilbert.)

estruction during their burial in the growing reef. In other instanc
ie coral masses represent remnants only, the greater portions havi
een broken down and worn away by the waves, or dissolved by tl
cean waters, soon after their formation. At various points there a



ig. 178.—Diagrammatic section showing the relations of various sorts of rock Genesee Falls. (Hall.)

etached fragments showing various degrees of wear, together wit
oarse and fine detritus, the product of coral comminution. The
ombine to make up the mass of the reef-rock. Locally there

evidence that some of the limestone after having once been solidified was broken up by the waves and re-deposited, forming a coarse, brecciated mass. In such cases the spaces between the fragments are often filled with fine detritus in which fossil shells sometimes occur, as though the shell-bearing animals had sought the protection of these sheltered nooks, or as if their shells had been driven thither by the waves. Evidences of wave-worn hollows and recesses in the reefs may also be found, showing that waves were then wearing, as now, the summits of rock-masses which were so slightly submerged as to come within the limits of their action.

The deposits between and about the ancient Wisconsin reefs are similarly instructive. On the sides and at the bases there accumulated a mixture of shell and coral fragments and calcareous sands growing finer and finer as the distance from the parent reef increased, and the slope of the bottom became more gentle, until at a distance, having passed through the several granular stages, there was a gradation into white calcareous mud, which spread itself widely over the sea-bottom around the reefs and between them and the adjacent land. This fine calcareous sediment ultimately gave rise to the compact white limestone of the region.

On the submarine plains immediately bordering the reefs flourished many forms of life which secrete lime carbonate. Mollusks and crinoids eem to have been more abundant here than upon the reefs themselves. Over the white mud-flats beyond there seems to have been a relative paucity of life, the reef-frequenting forms being especially rare.

In the ancient Niagara seas, therefore, at least four phases of limestone were in process of accumulation simultaneously, viz.: (1) that composed of coral which still remains unbroken; (2) that composed of masses of coral partly disrupted; (3) that made up of the granular products of shell and coral grinding; and (4) that made up of the still iner products of comminution, all derived from essentially the same source, the secretions of the reef life. To this category should perhaps be added (5) the brecciated limestone, made up of the broken and recemented fragments of beds which had been disrupted, and (6) the oölitic limestone which occurs at some points in this and many other limestone formations. The especial feature of this variety of limestone (Fig. 179) is that it is made of tiny concretions of lime carbonate precipitated from solution about nuclei of any sort. Recent observations have shown that the conspicuous beds of chert nodule dolomitic Niagara limestone of the Chicago area are in reali sponge beds. The minute spicular structure of these organis be frequently detected under the microscope in thin sections nodules (Fig. 179*a*), although in most of them these structur been nearly or wholly obliterated.[1]

East of the Appalachians and west of the Mississippi the tion of strata of Niagara age is not generally known in detail.

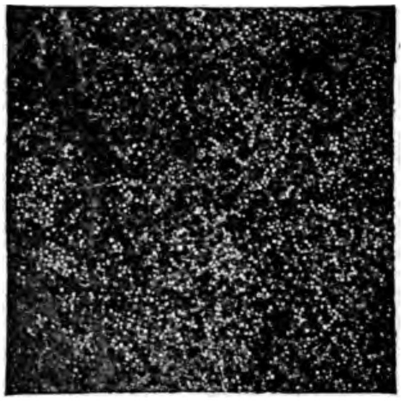


FIG. 179.—Oölitic limestone.

stones which are perhaps referable to the Niagara occur Hampshire and Maine,[2] and in the Provinces between these St the St. Lawrence. In Nova Scotia the formations of the epoch are represented by 1300 feet of shales, affording anot tration of the fact that very different sorts of rock may be accu in different regions at the same time.

Like the older formations of the Silurian, the Niagara has identified with certainty in the western part of the continent.

Unlike the preceding formations of the Silurian, the Ni not thicker in the east than elsewhere. In the east, indeed, w formation is exposed it has a thickness of but 100 to 300 feet, Wisconsin [3] it attains a maximum of 800 feet (probably includ Clinton), all of which is limestone. It would appear that the la the eastern border of the continent was not yielding abund ments to the sea lying west of it. This was probably because the land was low, and it may have been low either because it had sunk or because it had been nearly base-leveled in the preceding epochs. The slight thickness of limestone in the east (New York) as compared with the west (Wisconsin) remains to be accounted for. If the Niagara of the west, as commonly classified, includes beds which are the time-equivalents of the Clinton of the east, this would help to account for the greater thickness of the Niagara of the west. Again, it may be that the sorts of life which produce limestone were more abundant in the west, a suggestion which the coral reefs, as well as other fossils of that region, strengthen.

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[1] G. F. Harris, personal communication.

[2] Williams, Bull. 165, U. S. Geol. Surv.

[3] Geol. of Wis., Vols. I and II.

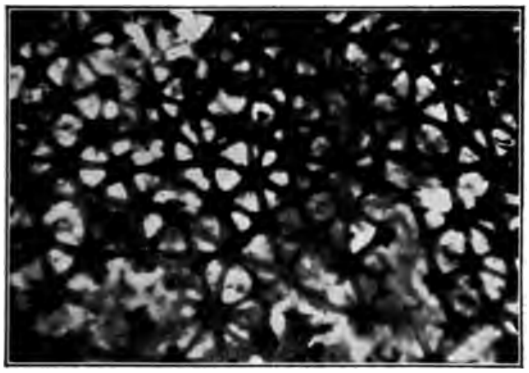

Fig. 179a.—Photograph of a section of a chert nodule from the Niagara limestone near Chicago, showing sponge structure. (From G. F Harris.)

The Guelph dolomite (Fig. 180) is distinguished from the Lockport dolomite in western New York by the presence of a different fauna. This fauna is, however, not restricted to beds overlying the Lockport dolomite, but occurs as represented in Fig. 180. This section appears to mean that the locality where it occurs was near the border of two regions inhabited by different but contemporaneous faunas, and that these faunas alternately had the advantage in the struggle for dominance.[1] If this interpretation be correct, the Guelph and Lockport dolomites are, in part at least, contemporaneous.

While the Niagaran beds of the interior are in general nearly horizontal, they are frequently domed so as to give the beds a high angle of dip. This is true at some points in eastern Wisconsin, about Chic and at points in Indiana. (Fig. 181.)

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[1] New York State Museum, Memoir 5, 1903, pp. 4–22.

THE SALINA (CAYUGAN) SERIES.

The Salina series.—The formation or group of formations succeeding the wide-spread Niagara limestone differs from it so wi

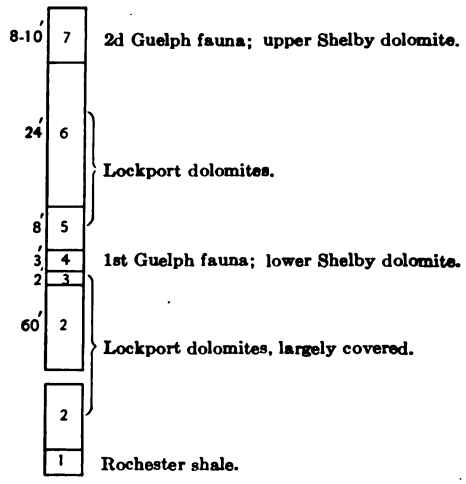
8-10'
7
2d Guelph fauna; upper Shelby dolomite.
24'
6
Lockport dolomites.
8'
5
3'
4
1st Guelph fauna; lower Shelby dolomite.
2'
3
60'
2
Lockport dolomites, largely covered.
2
1
Rochester shale.

FIG. 180.—Figure showing the relations of the Guelph to the other members Niagaran series. (New York Geol. Surv.)

both in distribution and character as to indicate that conside geographic changes had intervened. It extends somewhat fa

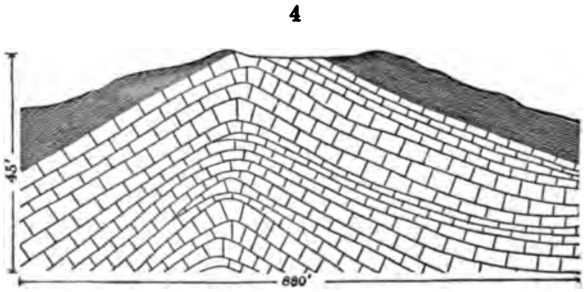

FIG. 181.—The Wabash dome in the Niagara limestone. (Kindle.)

east than the Niagara, and occurs in the Appalachians of Pen vania and farther south, where the Niagara is not known to be ent. To the west, on the other hand, the Salina formation is restricted to much narrower limits than the Niagara. Like the latter, it underlies much of southern and southwestern New York, and probably western Pennsylvania as well, and extends west into Ohio. It is also present in Ontario, and extends thence to the northern extremity of the southern peninsula of Michigan, and to the eastern border of Wisconsin, but it is not known in Illinois, or at any point farther west in the basin of the Mississippi. If it now exists in these States, it has not been identified.

The absence of the Salina formation from so great an area where the Niagara is present, points to the emergence of a considerable area in the Mississippi basin at the close of the Niagara epoch, and the nature of the Salina series, where present, shows that geographic relations were greatly altered. A map showing the relations of land and water during the Salina epoch would show a great increase in land over that shown in Fig. 174.

In the east, the Salina group embraces three principal varieties of rock—limestone, shale, and rock salt. With these formations, some gypsum, the usual concomitant of salt beds, is associated. Shales constitute the larger part of the group, and seem to have originated after the fashion of shales in general, but their meager content of fossils seems to point to their deposition under conditions unfavorable for life.

The salt is widely distributed. It is known to occur at many points in New York within an area 9,000 to 10,000 square miles in extent, single beds of it being locally 40 to 80 feet in thickness. Several beds of it sometimes occur one above another, interstratified with other sorts of rock, and their aggregate thickness sometimes reaches as much as 100 feet. In some sections, therefore, the salt makes a very considerable fraction of the total thickness of the series. The same relations hold still farther west. Near Cleveland, four salt beds, 50 feet and less in thickness, are interstratified with 500 feet of shales belonging to this period.

The presence of salt beds in New York and Ohio indicates that during the movements which took place about the close of the Niagara period, great lagoons or inclosed seas were formed. In these lagoons it is believed the red shales and other formations of the Salina group were deposited. Had the climate of the region been as moist as that f the present time, these lagoons would hardly have become abn nally saline. The fact that salt was precipitated in such quantit s therefore an indication of aridity. Data are not at hand for det nining whether the aridity was local or general. Whenever and whe ver the water of these inclosed seas reached the saturation-po or salt, its precipitation began. Occasional incursions of the ringing in new supplies of salt water, followed by periods when agoons were cut off from the sea, and suffered rapid evaporat would seem to meet the conditions demanded for the formation he salt. So also would a slight continuous connection with the uch that the inflow of sea-water into the basin did not balance xcess of evaporation over precipitation in the basin area. Bed alt 40 to 80 feet thick imply the evaporation of 3000 to 6000 fee normal sea-water.

It is not known how nearly continuous the beds of salt are in area within which they occur. Knowledge concerning them is obta only from borings, for they are buried beneath great thicknesse younger rock. Since the strata dip to the south, the salt bed farther and farther beneath the surface in that direction. Mucl the salt of commerce which comes from New York is not derived in diately from the salt beds, but from the waters of salt wells. water of these wells probably became briny by passing over or thr the salt beds, or over or through strata of shale through which sa disseminated.

Gypsum is often associated with sedimentary formations depos in inclosed seas. It is much less soluble in waters which are ne saturated with salt than in sea-water. Since it is usually pre in saline waters, it is likely to be precipitated as the water approa the saturation point for salt. In keeping with these general f it is present in the Salina series. Some of the gypsum is probabl secondary origin, being the result of the reaction of sulphuric aci calcium carbonate.

The limestone of the Salina proper is largely contemporaneous the shales and salt beds. It is thickest where they are thin, and where they are thickest. It contains few fossils, and may be a chen precipitate. Its relations to the shales and salt beds are such a indicate that the areas of accumulation of the several sorts of material were shifted from time to time, as if by gentle changes of level of land or water.

The thickness of the beds of the Salina group is considerable, being about 1500 feet near Ithaca, and still more in the mountains of Pennsylvania, where it attains its maximum development, though free from salt. From central New York the formation thins both to the east and west.

The sequence of changes in the Salina region of New York is indicated by the following table:[1]

Decreasing Salinity.	H G	Niagara-Guelph fauna	Cobleskill
	F	Waterlime with Eurypterus	Salina
	E	Gypseous shales	
		Beds of rock salt	
Increasing Salinity.	D	Gypseous shales	
	C	Pittsford shale with Eurypterus	
	B	Guelph fauna	Niagaran
	A	Niagara (Lockport) fauna	

Associated formations.—Above the Salina proper of New York, there is a thin (150 feet maximum) formation of limestone, the Waterlime (Cobleskill, Rondout, Manlius, etc.), which is generally regarded as a part of the Silurian system. The name Waterlime has reference to the fact that the limestone is the source of hydraulic cement, though it is by no means everywhere useful for this purpose, and many other limestone formations are similarly used. The Waterlime is more wide-spread than the Salina, extending westward through Ohio (where it is often shaly) to Indiana (Kokomo) and to Wisconsin. Both its distribution and its character show that the eastern interior was again more generally submerged than during the deposition of the salt-bearing series which preceded. In the Waterlime group, especially its lower portion (Cobleskill), the Niagara-Guelph fauna reappears (see p. 386), indicating a return of marine conditions, and of a fauna which had been excluded for a time from this region because of the salinity of the waters. The sequence of conditions during the Salina is shown diagrammatically above, and the relations of the Silurian and Early Devonian formations on opposite sides of the barrier which separated eastern from central New York, are suggested by Fig. 182.

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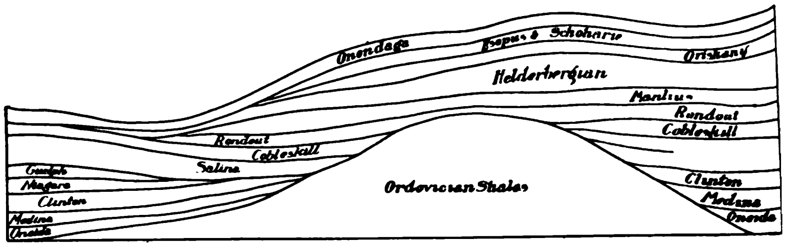
[1] Hartnagel, Bull. 69, N. Y. State Museum, p. 1159.

Silurian in the West.

The Silurian and Ordovician systems have been usually mapped ɔne under the former name in the area west of the Great Plains. ʳarious points in this region there is, between the Ordovician be ınd the Devonian above, a series of sedimentary beds poor in fos The character of the fossils being indecisive, the age of the beds has ɔeen certainly determined. Some of them may be Silurian, thoı



ꟳIG. 182.—Diagram showing overlaps and succession of formations of the eas interior sea during the Silurian and Early Devonian periods. (Hartnagel.)

n many regions all appear to be referable to the Ordovician. If t ıre to be correlated with the Silurian, the Ordovician types of life r ıave lingered on in the west much longer than in the east. If the S ·ian is really absent from all the areas where its presence is not kno t would appear that a large part of western North America · and during the Silurian period. The Silurian system has not b dentified in the fine sections of the Colorado canyon in Arizona, ; ɔrobably does not exist there. This may mean that either this ɩ ɔf the west was land during the Silurian period, or that such Silur ormations as were deposited here were subsequently removed ɛrosion during an interval of emergence. Silurian beds are repor rom the Fort Apache region of Arizona,[1] from southern California ɛ Nevada,[2] and from the Seward Peninsula of Alaska.[3] They are dou ully reported from the Canadian Rockies, but the beds in quest ɜeem to belong to the same system as many other western beds, refer: ɛntatively to the Ordovician on the basis of their fossils.[4]

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[1] Reagan, Am. Geol., Vol. 32, 1903, p. 278.

[2] Spurr, Bull. 208, U. S. Geol. Surv., pp. 70, 86, and 202.

[3] Collier, Professional Paper No. 2, U. S. Geol. Surv.

[4] Dawson, Bull. Geol. Soc. Am., Vol. 12, p. 68.

The Helderberg formation.—It has been customary in the past
regard the Helderberg formation as a part of the Silurian
stem, though its reference to the Devonian has often been sug-
sted. The fossils of the Helderberg formation are commonly
garded as pointing to alliance with the Devonian faunas, rather
an with the Silurian.[1] By this standard, therefore, the reference
the Helderberg formation to the Devonian system seems the
re appropriate.

SUMMARY

As in the case of all preceding systems of the Paleozoic, the greater
cknesses of Silurian strata occur in the Appalachian mountain system,
re the Medina and Oneida have a thickness of 1500 feet, the Clinton
2000 feet, and the Niagara and Salina of 1500 feet (central New York),
ing the Silurian system a thickness of about a mile, though this is
more than its average. In Maryland its thickness is between 2000
l 2500 feet. It is chiefly clastic below, with limestone above.[2] Over
interior, the system is relatively thin, being measured by hundreds
eet rather than by thousands. In keeping with these variations in
kness, the Silurian along the Appalachian belt is largely of clastic
iments of shallow-water origin, while that of the interior originated
lear, though not necessarily deep water. During most, if not all, the
iod, the Appalachian trough was shut off from free communication
h the interior sea, but connected with the Atlantic, perhaps by way
he present Chesapeake region. The great thicknesses of strata in the
tern mountain region were deposited in this Appalachian trough.
ce all or most of them were deposited in shallow water, they are
ally thought to point to the conclusion that the trough was sink-
, and that at a rate comparable to that at which the sediments
umulated. This view may, however, need to be qualified by con-
rations such as those suggested on page 257. So far as local sinking
k place, the accumulation itself, as already suggested, may have

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[1] Clarke, Review of the Hercynian fauna, 42d Rept. N. Y. State Mus., p. 408. See
views of Tschernychew, Am. Geol., Vol. XIV, 1894, p. 119; Schuchert, Bull.
L Soc. Am., Vol. II, pp. 241–332; Williams (who advocates the opposite view),
, pp. 338–346; and Kayser, Geologische Formationskunde, zweite Auflage.
Prosser, Jour. of Geol., Vol. IX, pp. 410–15.

been the cause, or one of the causes, of the subsidence. Coinci with the downward warping of the trough, the adjacent land area w supplied the sediments, was probably warping upward steadily periodically.

The history of the Silurian period, as now understood, involves, a general submergence of the eastern part of the United States wes Appalachia, by which the sea became more and more wide-sp until the close of the Niagara epoch; (2) a partial withdrawal of sea from the same area during the Salina epoch; and (3) a poss extension of the sea at the close of the Salina epoch. There doubtless many minor oscillations of level not distinctly recorde the rocks, or, at any rate, not yet distinctly determined.

Of the sediments deposited along the Atlantic coast on the eas border of Appalachia during the Silurian period little is known. T have not been identified at any point within the present land south of New England. From this it is inferred that the Silurian s south of New England was farther east than that of to-day, and the Trans-Appalachian Silurian strata are still beneath the sea, de buried by younger formations. There is no certain knowledge, howe that the Silurian seas did not cover some part of the present land east of the mountains. If so, such formations as were made have removed by erosion, or transformed by metamorphism so that have not been recognized, or lie buried beneath later formations. ther north, as in New England and beyond, the sediments of this pe seem to have accumulated partly in bays which affected the coast, partly along the border of the open sea.

Outcrops.—The principal areas where the Niagaran series ap at the surface are shown on the map, Fig. 174. A map showing outcrop of the system as a whole would not be very different (see I I). Fig. 174 shows also the relations of the Silurian to older syst and hazards a conjecture as to their probable occurrence where concealed. The principles underlying the distribution of outc have already been discussed (p. 252 *et seq.*).

Former extent and general stratigraphy.—The present margi the several Silurian formations are not their original margins, for exposed parts have suffered erosion, and the erosion of dipping as already explained, shifts their outcrops. In some localities t are certain reliable data for estimating the former extension of formations. In Wisconsin, for example, remnants (outliers, *a*, *b*, *c*) of the Niagara are found far beyond the main body (*S*, Fig. 183) of

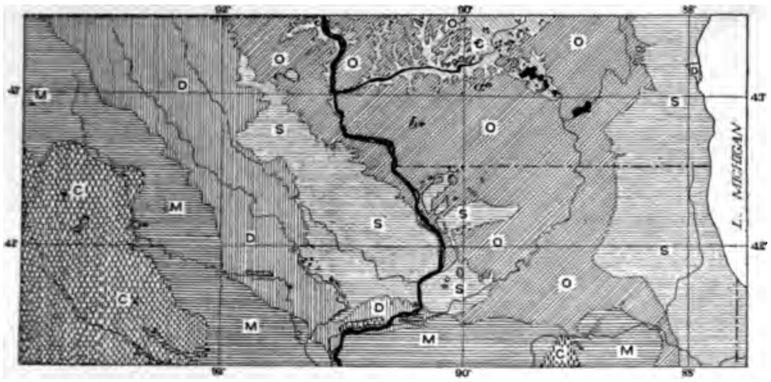


FIG. 183.—Map showing the surface distribution of Silurian, Ordovician, and other formations in southern Wisconsin, northern Illinois, and eastern Iowa. €=Cambrian; *O*=Ordovician; *S*=Niagara, and *a*, *b*, *c* are outliers of *S*; *M*=Mississippian; and *C*=Carboniferous.

the formation as it now exists. These remnants fix at least a minimum limit to the original extension of the formation. The stratigraphical relations are indicated by the accompanying section (Fig. 184), which

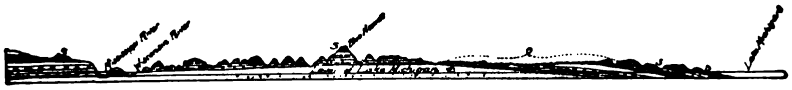
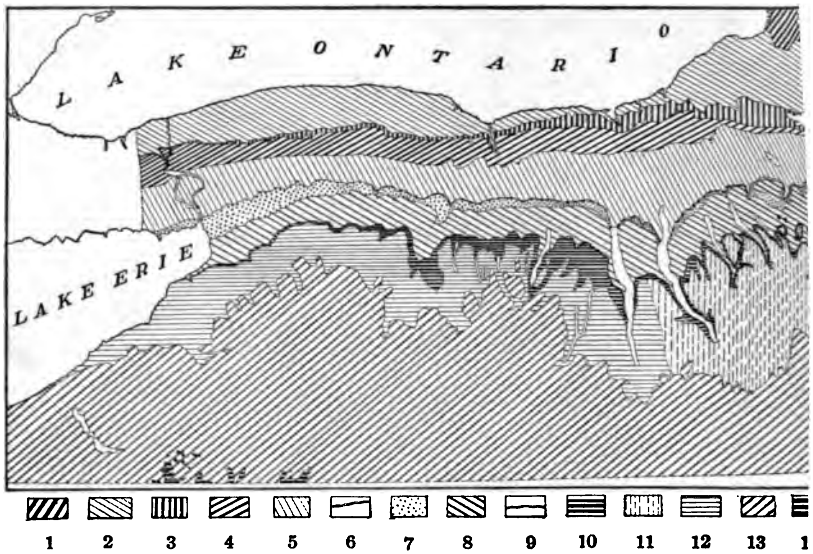


FIG. 184.—Section showing the structure of the Silurian and other beds in Wisconsin. €=Cambrian; *O*=Ordovician; *S*=Silurian; and *D*=Devonian. The black belt at the surface=glacial drift, etc. (Wis. Geol. Surv.)

at once suggests the basis for the estimate. Farther north the Silurian formations appear to have been completely removed from great areas which they once covered.

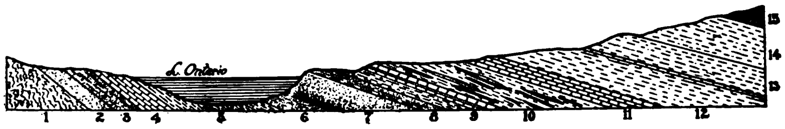
The map (Fig. 185) of a part of New York shows the relations of the outcrops of the several Silurian formations in the western part of that State. Their former northward extension can only be conjectured, but it was probably considerable. Fig. 186 shows the stratigraphic relations of the beds shown on the map, the section being from north to south. Figs. 184 and 186 fairly illustrate the stratigraphic relations of the Silurian in the interior generally. Their stratigraphic relations in the Appalachian mountains are illustrated by Figs. 138 and 139, where he upper part of the formation marked *S* is often Silurian (the lo art being Ordovician).



'IG. 185.—Map of a portion of the State of New York showing the surface distribu of the various Silurian and Devonian formations. 1=Ordovician; 2 to Silurian; 6 to 13=Devonian; 14=Mississippian.

Sections of the Silurian in various regions are given on pp. 317– nd in the Appendix, Vol. III.

Igneous rocks.—At few points in North America have igneous rc f Silurian age been identified. The Silurian formations are so



'IG. 186.—Section showing the structure of Silurian and Devonian beds in wes New York. 1=Pre-Cambrian; 2=Cambrian (Potsdam); 3 to 6=Ordovic Calciferous, Trenton, Utica, and Hudson River respectively; 7 to 10=Silur Oneida and Medina, Clinton, Niagara, and Salina respectively; 11 to 14=D nian, Helderberg, Hamilton, Genesee, Portage, Catskill, and Chemung respectiv and 15=Carboniferous.

imes affected by igneous intrusions, but the date of the intrusion enerally uncertain. Some of the igneous rocks of New Brunswick hought to be of Silurian age, and perhaps some of those of Nova Sc and Maine.[1] In the Fox Islands of Maine, the Niagaran age of some igneous rocks seems to be clearly indicated.[2]

CLOSE OF THE SILURIAN.

The closing stages of the Silurian were marked by the withdrawal of the epicontinental sea from considerable areas of the eastern interior which had been submerged during the Niagaran. The sea appears to have continued to cover the area of the Appalachian trough. Orogenic disturbances at this time seem to have been essentially wanting in North America. The geographic changes at the close of the Silurian appear to have been greater than those which occurred during the period, dividing it into epochs and stages, but they were notably less than those which closed the Ordovician. It follows that the Silurian system is less distinctly separated from the Devonian above than from the Ordovician beneath.

FOREIGN SILURIAN.

In Europe the Silurian strata have a distribution similar to that of the Ordovician, though they are wanting in some regions where the latter are present. As in the Cambrian and Ordovician periods, the continent seems to have been divided into two distinct geographic provinces. Within the northern, the Silurian strata are rather less widely distributed than those of the preceding system, especially in eastern and northeastern Russia. The fact that the Silurian strata do not appear at the surface over wide areas does not indicate their general absence so much as their widespread concealment. They are believed to be widely distributed beneath the younger beds between the Baltic and the Urals, as well as farther east. In most of the northern province, outside of Britain the system has been little deformed.

In the southern province, the Silurian formations are not widely exposed, appearing in small areas only amidst formations of lesser age. In contrast with the Silurian rocks of the northern province, those of the southern are much deformed.

The Silurian (the name comes from the name of an ancient tribe of Britain, the *Silures*) formations of Europe, especially of the northern province, are more largely composed of limestone than those of Ordovician, suggesting clearer seas. In Great Britain, the three cipal groups of the system, commencing below, are (1) the Llando (2) the Wenlock, and (3) the Ludlow.

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[1] Williams, H. S. Jour. of Geol., Vol. II, pp. 16–18.

[2] Smith, G. O. Geol. of the Fox Islands, Me., Rev. Am. Geol., Vol. XIX, p. 214.

In general the Silurian rests conformably on the Ordovician, this is not true in the British Isles, where the younger system on the upturned and eroded strata of the older. As in America, system contains little igneous rock.

Its thickness is less than that of either of the two preceding syst being but 3000 to 5000 feet in Great Britain. It is perhaps less to add that this lesser thickness does not necessarily denc shorter period of time. It may equally well stand for a less rate of accumulation.

The Ordovician and Silurian of other continents have not generally distinguished. The equivalents of the two systems as tinguished in Europe and North America probably occur in al less well-known continents. Strangely enough, the faunal resemb of the Silurian of other regions, even of other continents, to th the northern province of Europe, is stronger than that of this pro to the southern province of the same continent.

CLIMATE.[1]

There is nothing to indicate great diversity of temperature i Silurian period, and much to suggest that its uniformity exte through great ranges of latitude, for the fossils of warm-temp latitudes are in part the same as those in Arctic regions. Ce regions (New York and vicinity) appear to have been tempo (Salina epoch) arid.

THE SILURIAN LIFE.

The extensive withdrawal of the sea from the surface of the American Continent at the close of the Ordovician period very gr reduced the area of shallow water available for the forms of life had so richly peopled it during that period. A repressive evol of much severity necessarily followed. This constitutes the biological feature of the transition from the Ordovician to the rian. With the extensive re-invasion of the interior by the Mid-Silu sea, there followed an expansional evolution of the shallow-water fauna, and this constitutes the great biological feature of the middle of the period. Toward the close of the period there was another but less considerable restriction of the epicontinental sea, complicated with intense salinity in the eastern interior region, and there followed a second repressive evolution marked by special features. Through this, the fauna passed into the Devonian type, and the marine life-history of the Silurian was closed.

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[1] Schwarz, Jour. Geol., 1906.

These major biological movements were varied and complicated by many minor movements upon which we cannot dwell. These generalizations relate solely to the shallow-water marine life. The history of the land life should theoretically have been the reciprocal of that of the sea; for as the sea contracted the land expanded, and an expansional evolution of land life should have run hand in hand with the restrictional evolution of the sea life. This was probably the fact, but the record of the land life is too meager to demonstrate it.

It is not probable that the life of the ocean surface or of the abysmal depths was sensibly changed by these continental modifications, but there is practically no evidence bearing on this point, for, as ever to be borne in mind, the geological record of marine life is almost wholly that of the shore tracts and the epicontinental seas.

Had the physical changes of the continent at the close of the Silurian period been as pronounced as those at its beginning, it would have constituted an ideal cycle, consisting of an advance, a dominance, and a retreat of the sea, attended by expansional, cosmopolitan, and restrictional phases of shallow-water life, and would thus have rounded out a typical period. Starting with a transformed remnant of the previous fauna distributed along a skirting shoal tract and gathered in a few bordering embayments which harbored it during the vicissitudes of the transition, the life expanded with the expanding epicontinental seas, attained a cosmopolitan prevalence in the Mid-Silurian, and later, with the retraction of the sea, shrank again to meager proportions and was transformed into the initiative fauna of the next period.

The Transition from the Ordovician.

Severely restricted as the shallow-water life must have been during the stage of the greatest sea withdrawal, the record probably makes

it appear more impoverished than it really was. The shore tr
were then far out on the borders of the continental platform, and
deposits there made were buried beneath later deposits when the
readvanced, and have been specially subject to further burial by
sequent border deposits. Large portions of these tracts are prob
now under the sea. They are, therefore, of all epicontinental dep
least accessible to observation.

Aside from the lessened area, the life conditions were prob
less favorable, area for area, than in the stage of sea expansion
the wash from the land was presumably augmented by the incr
land area and the greater relief of the land caused by the low
of the sea-level, if not also, as is probable, by the upward bowi
the continental surface. The increased detritus poured by the
into the coast belt probably inhibited some forms of life, injured ot
and helped but a few. Some of the basins or embayments were d
less affected by too great freshness of water and some by too
salinity, and what was probably more unfavorable for life, by
nations from the one to the other.

These general characterizations find exemplification in the m
ness of the faunas of the Shawangunk grit, the Oneida conglom
and the Medina sandstone, all of which are very barren of fossils. G
ing that some part of this barrenness may be due to the disso
away of relics once contained in the beds, there can be little
of an original barrenness, for whatever may be true of the coarse
stones, there is no reason to assume exceptional solution of o
substances in the abundant shales and fine-grained argillaceous
stones.

In the earliest beds referred to the Medina in the eastern int
there are a few lingering Ordovician species. Then follows the
mass of the Medina formation in which practically no determi
life relics appear, while near the top of the deposit a meager fau
the post-transition type initiates the distinctive Silurian f
Scarcely more than a dozen species of invertebrates have been i
fied, and these have a pauperitic aspect that seems to tell of the
conditions under which they lived. The very fact that the M
shales and sandstones are prevailingly red, probably tells a t
hostility to life, but we cannot read it with much assurance at pr

It will claim consideration in connection with the great red deposits of later periods.

Universally adverse conditions are not, however, to be assumed during the transition epoch. The very drawing down of the waters on the borders of the continent must inevitably have so shallowed the sea on some deeply submerged tracts as to have made them congenial ground for the retreating faunas of the interior. This might well be true of deep embayments on the continental border. The Gulf of St. Lawrence seems to have been a notable example, and to have constituted a harbor of refuge for the retiring hosts of the interior. In it, as shown by the deposits of Anticosti, Ordovician species lived on for varying lengths of time and mingled with Silurian species as they developed, and so recorded the transition. This appears to have been the breeding-ground of one of the provincial phases of the Silurian fauna, but it is not at all probable that it was the only one. Doubtless there were other similar embayments, and the whole coast tract probably made its contribution to the Silurian fauna; but south of the St. Lawrence the record of the phases of life transitional from Ordovician to Silurian is not at command. The main Silurian fauna of the interior apparently did not arise from that of the St. Lawrence embayment or of the Atlantic border, but developed somewhere at the north, or came in from the eastern continent.

The Expansional Stage and the Mid-Silurian Fauna.

As the sea slowly crept out upon the face of the continent toward the middle of the period, increasing room and more congenial conditions for most forms of shallow-water life afforded the means of a new expansional evolution, and this finds expression in the Niagaran fauna. This is comparable to the expansional stage of the Mid-Ordovician fauna. The families and classes remained nearly the same as in Ordovician time, but the majority of the genera were new, as were nearly all the species. A very few species of extraordinary longevity bridge the great interval, such as *Leptæna rhomboidalis* (Fig. 163, *w*), *Plectambonites sericeus* (Fig. 163, *x*), and *Platystrophia biforata*. These stand out as conspicuous examples of extraordinary persistence, though even they had changed somewhat. In general there was a biological advance, but regarding the particular classes, some had risen and

me had fallen, while all had undergone a change. The more conspici
ıs features of these changes claim attention.

Echinoderms: the blastoids.—A distinguishing feature of the Siluria
una was the rich and varied development of the echinoderms, invol
g at once the rise or the decline of old forms and the introductic
new ones. To the five classes present in the Ordovician, there w
ɪw added the blastoids, and the full list of classes adapted to fossil
tion was completed. The new class consisted of symmetrical, bu
;e forms, with a calyx of a definite number of plates, very regular
ıd beautifully arranged in pentamerous order, but without true arm
shown in Fig. 187, *i*. Only two genera of blastoids, so far as know
ere as yet present, but in the two succeeding periods a rapid develo
ent was achieved, followed by a swift decline.

The rise of the crinoids.—The appearance of the blastoids w
mark of advance; but the dominant feature was the rise of the cri
ds. They attained such abundance in certain congenial localiti
ıat their fragments formed the main substance of the limestoı
hese spots became veritable "flower-beds" of "stone lilies," a
rtain localities, as Lockport, N. Y., Waldron and St. Paul, Ind., F
ne, Wis., Chicago, Ill., Gotland, Sweden, and Dudley, England, ha
ecome noted as peculiarly rich crinoidal fields, where beautiful a
ıried forms grew in groves, as it were. The assemblage of spec
each of these noted localities had its own peculiarities, but the gen
ere usually much the same. A few Silurian crinoids are shown
ig. 187, *a*, *b*, *c*, *d*, *e*, but no such limited selection of figures can
ıstice to the variety and beauty of form they displayed.[1] The wi
ıfferences of those illustrated, however, gives some hint of the devel
ent of the class. Among the notable features was a large projecti
ıbe whose apparent function was to carry the used waters of t
ɔdy cavity away for discharge at a distance from the food groov
ith an apparent hygienic purpose. In certain cases, this tube v
ıriously expanded above, the plates spreading into a broad umbrel
;e canopy with the apparent purpose of still more effectively p
enting the mingling of the used and unused water. A new featı
as the consolidation of the plates at the base of the calyx, imparti

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[1] For a fine series of illustrations see the classic work of Wachsmuth & Spring
ıe North American Crinoidea Camerata, Mus. Comp. Zool., Cambridge, Mass., V
XI, 1897.

added strength to it. Spines were occasional features and doubtless served a defensive purpose. Some species were notably ornamented by various figures upon the exterior of the plates, the function of which can only be conjectured. The arms of the camerate crinoids, which, in Ordovician times, were largely formed of a single series of plates, nearly all came to have a double series in the Silurian. Notwithstanding these and other expressions of progress, there remained many remnants of the more primitive characters, indicating that the class had not yet reached its structural climax. The lower orders of the class were still present, but in diminished numbers. The decline of these and the rise of the higher types is in itself a mark of progress. At the same time, the continued existence of the lower types teaches that the introduction of the higher was not at once fatal to the welfare of the lower.

The cystoids.—Though the cystoids passed their climax in the Ordovician, they continued to be abundant in the Silurian, and many attained larger sizes than are known to have been reached before. They show in some phases a tendency to greater regularity in the arrangement of the plates, as though even they felt the influence of the causes that made for order and symmetry, so well expressed in the crinoids and blastoids; but on the whole, irregularity continued to characterize them (Fig. 187, *f*, *g* and *h*).

Other echinoderms.—The starfishes appear to have made little progress and to have had no large place in the fauna; the serpent stars and the echinoids had even less. It is important to note these slow developments of types that came to be prominent very much later, for it possibly represents a general fact, viz., that great classes were really slow in their evolution, however suddenly they may seem to have come into existence. It is not impossible that the ascents of the cystoids and crinoids to their climaxes would be found equally as prolonged as those of their kin if we could trace them back through their full histories. Just a little greater imperfection in the record would have eliminated all trace of the ophiuroids and echinoids in these early periods and would have made their appearance in abundance at a later period seem sudden and remarkable. This suggestion is not to be accepted as an affirmation, for there are some strong grounds for believing that evolution was sometimes really rapid relatively.

The continued importance of the brachiopods.—The brachiopods

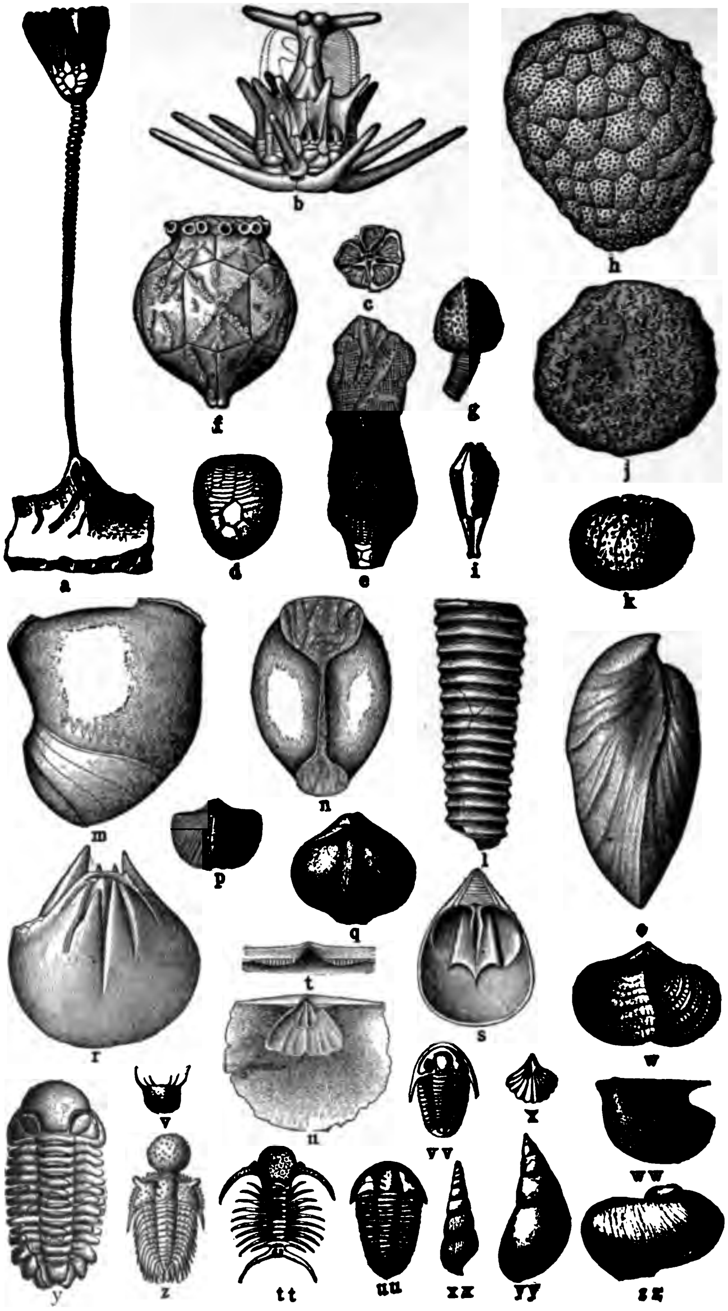

FIG. 187.—(See opposite page for explanation of figure.)

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EXPLANATION OF FIG. 187.—*Crinoidea: a, Eucalyptocrinus crassus* Hall, a complete crinoid, showing root, stem, and body; *b, Callicrinus murchisonianus* Ang., showing extraordinary spinose ornamentation; *c, Petalocrinus mirabilis* Weller, showing a remarkable type of arm differentiation, the arms being consolidated into five triangular plate-like bodies; *d, Lecanocrinus macropetalus* Hall, one of the articulate crinoids; *e, Crotalocrinus pulcher* (His.), a crinoid with remarkably differentiated arms. *Cystoidea: f, Caryocrinus ornatus* Say., a cystoid with regularly arranged body-plates; the pores may be seen arranged in radiating lines from the centres of the plates; *g, Callicystis jewetti* Hall, a cystoid with unsymmetrical arrangement of plates, the arm furrows recumbent, the pores arranged in groups; *h, Holocystites adiapatus* Miller, a cystoid with irregularly arranged plates and scattered pores. *Blastoidea: i, Troostocrinus reinwardtii* (Troost), showing the typical bud-shaped form of these organisms. *Sponges: j, Astræospongia meniscus* Roem., a saucer-shaped sponge with exceptionally large spicules; *k, Astylospongia præmorsa* (Goldf.), a globular sponge showing the osculum above and the ends of the water canals. *Cephalopoda: l, Orthoceras annulatum* Sow., a straight chambered shell with annulations; *m–n, Phragmoceras nestor* Hall, lateral and end views of a curved chambered shell with peculiar constricted aperture. *Brachiopoda: o, Pentamerus oblongus* Murch., lateral view of an internal cast; *p, Spirifer niagarensis* (Con.), exterior view of the brachial or dorsal valve, with the cardinal area and beak of the pedicle or ventral valve showing above; *q, Spirifer radiatus* Sow., a view similar to the last. These two figures show the plicated and non-plicated spirifer shells, marked with fine radiating striæ; *r, Trimerella ohioensis* Meek, the internal cast of a highly differentiated inarticulate brachiopod, showing the finger-like casts of the excavations beneath the elevated muscular platforms; *s, Trimerella acuminata* Bill., the interior view of a pedicle or ventral valve, showing the elevated platform for muscular attachment, excavated beneath; *t, u, Stropheodonta profunda* Hall, interior of the pedicle or ventral valve, showing muscular impressions, cardinal area, delthyrium, and crenulated hinge line, with an enlarged view of the area and hinge; *v, Chonetes cornutus* (Hall), exterior view of pedicle or ventral valve, showing the cardinal spines; *w, Streptis grayi* (Dav.), exterior view of the brachial or dorsal valve, showing the cardinal area and beak of the opposite valve and the peculiar twisted form of the shell; *x, Rhynchotreta cuneata* (Dal.), exterior view of the brachial or dorsal valve, showing the beak and pedicle opening of the opposite valve. *Trilobita: y, Sphærexochus mirus* Bey., dorsal view; *z, Staurocephalus murchisoni* Barr, dorsal view, showing the peculiar globular anterior prolongation of the head; *tt, Deiphon forbesi* Barr, dorsal view of a peculiar trilobite having the pleural lobes much reduced; *uu, Calymene niagarensis* Hall, dorsal view of one of the commonest Silurian trilobites; *vv, Cyphaspis christyi* Hall, dorsal view. *Pelecypoda: ww, Pterinea emacerata* (Con.), exterior view of the left valve. *Gastropoda: xx, Loxonema leda* Hall; *yy, Subulites ventricosus* Hall; *zz, Platyostoma niagarensis* Hall, views of three types of Silurian coiled shells. (Weller.)

(Page 403)

stood the vicissitudes of the passage from the Ordovician to the Si rian with no loss to the prestige of the class, though they suffe an almost entire change of species and a very large change of gene When it is considered that the brachiopods were among the m resistant and conservative of the invertebrates, this large change species and genera emphasizes the stress of the conditions that c trolled the transition, as well as the biologic importance of the inter of transition.

The brachiopods remained the most abundant organisms of Mid-Silurian fauna, and shared with the crinoids, corals, and ceph pods the leading places. They had gained greatly in differentiat and had made some notable advances in structure. On the wh they were more robust and gave more obvious signs of abundant vita than in preceding periods. The curious concavo-convex forms less abundant, though not wanting. There was a great increase in spire-bearing genera. One of these, the *Spirifer*, named from fine brachial spires, is especially interesting. It had acquired a do provision against the forcing of its shell by developing a long h line at the back and a strong interlocking fold and sinus at the fr and, in addition, its biconvex shell was usually, though not alw well plicated (Fig. 187, *p*). The hinge line was not very greatly exte during the Silurian period, but became remarkably elongate in Devonian. The *Spirifers* appeared first in this period, but had greatest development in the two periods following.

It is interesting to note that along with the progressive dev ments there were retrogressive modifications. Most of the bra pods were mounted upon or attached by a pedicle which, while fi them to the bottom or to some object, gave them some degree of dom. But the *Crania* lost the functional use of the pedicel at an stage in the individual's life, and became cemented to other shell some like object, thus losing their freedom of motion. Notwithst ing this, the family was more abundant than in preceding per and the degenerate development was apparently advantageous.

Among the beaked shells, the *Pentamerus* family became the conspicuous and characteristic type (and gave name to certain b The *Pentamerus oblongus* (Fig. 187, *o*) was the largest and one o most common of the Silurian brachiopods. The *Pentamerus*, lik *Trimerella* (Fig. 187, *r*, *s*), developed remarkable processes on the int of the shell for the apparent purpose of shortening the muscles and giving them better attachment, and also to better adapt the interior to the visceral parts. Similar structural devices appear in other families. This mode of securing economy or advantage appeared in Ordovician times, though it was then rare.

Three brachiopod species which survived the vicissitudes of the transition from the Ordovician have already been mentioned. In the St. Lawrence embayment, where there was less disruption of continuity, at least two other species passed from the earlier period to the middle of the later. In Europe, the transition seems to have been easier, and more species survived it.

The decline of the bryozoans.—The coral-like bryozoans contributed much less material to the Silurian limestones than to those of the preceding period. This was partly because the whole class had declined in abundance, and partly because the more massive coralline type had fallen off relatively, and was largely replaced by the more delicate reticulate forms, such as *Fenestella* (Fig. 188, *f* and *g*). This change was probably advantageous, since a given number of individuals arranged in such a plexus would compass a larger area of food supply than in the more crowded form of the massive type, and at the same time would not seriously sacrifice their connection with one another. The incrusting forms of bryozoans became common, and often covered entirely the shells of mollusks and brachiopods.

The continued dominance of the cephalopods.—Except as possibly rivaled or overmastered by the little-known vertebrates, the cephalopods remained the most powerful of the known inhabitants of the Silurian seas. The large straight orthoceratites were less prevalent than before, though still common, while the curved and coiled forms were more numerous. The orthoceratites were more varied in external markings, some remaining smooth, some being fluted longitudinally, and some being annulated by rounded rings or wavy lines (Fig. 187, *l*), while others, by a combination of longitudinal and transverse markings, developed a reticulate ornamentation. Curved forms were the most numerous, and fully coiled forms were common. These were ornamented externally like the straight forms, but they were still quite plain in comparison with the remarkable ornamentation which the coiled forms assumed in later times. The apertures of the cephalopod shells of the Ordovician were usually circular or oval, but in the tance in the Silurian. They show advances in the preponderance of elevated spires, in increased variety of form, and often in their large sizes; but forms coiled in low spires, or in a plane, were still well represented (Fig. 187, *xx*, *yy*, *zz*). The pteropods were few, but the peculiar form *Conularia* was an interesting representative.

The pelecypods (Fig. 187, *ww*) were not as well represented in the Mid-Silurian beds as they were in the Ordovician, perhaps because the calcareous bottoms were less congenial to them. Some of the forms, however, were quite robust and displayed notable advances over previous forms.

Coral development and the inauguration of reef-building.—The prominence gained by the corals in suitable situations is one of the notable features of the Silurian fauna. In the Ordovician period the simple forms predominated over the compound. The ratio was now reversed, and the latter became very abundant. Among the notable types was the unique chain coral *Halysites* (Fig. 188, *c*), which was occasionally present in the Ordovician, but now became abundant; the honeycomb coral, *Favosites* (Fig. 188, *a*), accompanied by a group of allied genera; the organ-pipe coral, *Syringopora* (Fig. 188, *b*), and the cup coral, *Zaphrentis* (Fig. 188, *e*). A most peculiar coral of the simple class was *Goniophyllum* (Fig. 188, *d*), which instead of assuming the usual conical cup form took on a quadrangular shape and was provided with a cover (operculum) of four triangular plates hinged to the four sides of the cup's margin, so that when closed they formed a pyramid over the cup (Fig. 188, *d*; only two of the opercular plates shown). This was a protective device quite unknown among modern corals.

With their increase in abundance, the corals acquired the habit of associating themselves together, which resulted in the accumulation of coralline débris and the formation of reefs which, as they grew, rose above the common sea-bottom and secured the benefits of purer water and more active circulation. The known coral reefs appear to have stood some distance from shore, and to have been of the barrier type. Other life in great abundance and variety gathered upon or about these reefs, and they became rich depositories of the ancient faunas. The reef-forming habit appears to have been local rather than general, for over large tracts corals are found scattered in a markedly distributive fashion.

The initial decline of the trilobites.—No new families of trilobite far as known, were introduced during the period. Some new genei ere added and many new species, but these did not offset the di pearance of old ones, and the class, though still important, may l garded as having already entered upon its decline, so far as prev nce was concerned. This was not true apparently in respect to tl nk of certain leading types, which continued to advance in orgar tion. The highest Silurian forms were structurally equal, and pe ps superior, to any that preceded. The causes which induced tl cline in numbers do not seem to have been incompatible with inc dual and generic progress. Singularly erratic developments of for tended the decline of the trilobites, some features of which are shov Fig. 187, *y*, *z*, and *tt*. Less erratic types of trilobites are shown g. 187, *uu*, *vv*.

Other crustaceans.—In addition to the trilobites, ostracodes we t uncommon, and their little bivalve shells are sometimes abunda fossils. The ceratiocarids were also present. In view of the remar le development of a distinctly crustacean fauna in the last stag the period, the scantiness of these crustaceans in the Mid-Siluri och is notable.

Other marine invertebrates.—There was a most prolific field onges in western Tennessee, where the conditions were not or ngenial to their growth but favorable to their preservation. T ost abundant genus was *Astylospongia* (Fig. 187, *k*), a more or le herical form characterized by notably grooved surfaces. A sauc aped form, *Astræospongia meniscus* (Fig. 187, *j*), was also abunda Mr. G. F. Harris has recently found that sponges form the nuc chert nodules in the Chicago region. The genera *Astylospong ulocopina*, and *Hindia* have been identified.

The peculiar *Receptaculites* family, whose zoological affinities we ng in doubt, was still present, but chiefly represented by *Ischadit*

The graptolites had lost much of the importance they possess Ordovician times, and in the course of the period approached exti on. Sea worms are recognized through their jaws, tracks, and bu ws, and by the calcareous tubes which some of them secreted.

The scant record of the vertebrates.—In the earlier and Mid-S ian deposits very few relics of fishes and fish-like organisms ha en found, and these few are very imperfect. Near the close of t period, Silurian fishes were somewhat abundant and will be considered in connection with the closing Silurian fauna.

Marine plants.—Knowledge of marine plant life remains, as before, very unsatisfactory. While theoretically it must have been abundant, only obscure markings of the fucoidal type and a few evidences of higher forms have been found, and the interpretation of these is more or less doubtful.

Foreign Faunas and Migratory Relations.

Deferring the consideration of the peculiar closing fauna for a moment, the foreign relations of this rich and varied Mid-Silurian assemblage claim attention. The general progress of life on other continents, so far as known, was similar to that on the American, but perhaps less pronounced and symmetrical. A part of this similarity of progress was doubtless due to parallel evolution under similar general conditions, while a part was quite certainly due to intermigration Where the forms on different continents were merely similar, it is at present an open question whether the similarity was due to intermigration with modification or to independent evolution along similar lines; but where the forms on separate continents are specifically identical, especially if the species be peculiar and aberrant, it may safely be assumed that they had a common origin, and that migration is indicated. A striking case of this kind is presented by the quadrangular operculated coral *Goniophyllum pyramidale*, already mentioned (Fig. 188, *d*), which is found with identical idiosyncrasies in the island of Gothland in the Baltic Sea, and in Iowa. This evidence of migration is much strengthened by the presence in Gothland of three peculiar genera of crinoids that are also found in the upper Mississippi region. Besides such special cases, many prominent and familiar species were common to America and Europe, among which, neglecting the wide-ranging graptolites, were *Favosites gothlandica*, *Halysites catenulatus*, *Heliolites interstinctus*, *Dalmanella elegantula*, *Pentamerus oblongus*, *Spirifer radiatus*, *Rhynchotreta cuneata*, *Atrypa reticularis*, *Orthoceras annulatum*, *Homalonotus delphinocephalus*, and others. Some of these are also found in Asia, Australia, and New Zealand. Silurian genera occur in Bolivia, Peru, and Brazil, some species of which resemble North American and European species, but they have not been proved to be identical. Migratory connections in this case cannot be affirmed, but such connections

h Europe, Asia, Australia, and New Zealand may be assumed
ıblished. Since thirty or more species[1] are known to be comm
North America and Europe (the interior of North America aı
ɜden and Great Britain), and since these embrace a wide range
.era of very different habits, there is a strong presumption of rath
mate relations. The lines of intercommunication therefore becor
tters of interest biologically and geographically.

The migratory route.—The most marked community of species
erved, not between the Atlantic border fauna of America and th
the opposite coast of Europe, but between the interior Americ
na and that of Sweden and Great Britain. Singularly enoug
s the interior fauna that is pronouncedly intercontinental and c
politan in character. It has already been stated that the interi
seems to have had no free communication with the eastern a
ıthern coast regions, and that an extension to the far west is doul
while to the northward a chain of deposits, now separated by er
ı but probably once continuous, points to a broad thoroughfa
that direction (see map Fig. 174 and Fig. 190). This reaches
rth Greenland, from which, by way of Spitzbergen, Nova Zemb
l North Russia to Gothland in the Baltic, the steps are not excessive
at. The supposed connecting fauna has not, however, yet be
ntified in the imperfectly known Paleozoic beds of Spitzberge
va Zembla, and North Russia. There is a possible alternative l
y of the Iceland-Scotland submerged plateau, and still anoth
ɜrnative by way of the northwestern or Siberian route.

The paleontologic evidence favors a northern route, for the fau
the Arctic islands contains many species common to the Americ
ɜrior province and the Swedish-English province. It is significa
.t the Mid-Silurian fauna of Sweden more closely resembles th
the American interior than it does that of New York. Relati
the assigned northern thoroughfare, the New York area was a si
f or embayment less readily reached by immigrants from the nor
.n were the more open seas to the west. The very singular co
nity of aspect recently shown to exist between the faunas of Got
d, Sweden, and Dudley, England, and the Iowa-Illinois-Wiscons
ion give special emphasis to this.[2] *Crotalocrinus*, one of the mc

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[1] Phillips, Man. Geol., Pt. II, 1885, p. 122.

[2] Weller, Jour. of Geol., Vol. IV, 1896, pp. 166–173, and Vol. VI, 1898, pp. 692–7

singular and highly specialized genera of crinoids, together with the genus *Corymbocrinus,* are common to the Gothland and the Chicago faunas. *Petalocrinus,* another highly specialized genus, is common to Gothland, Iowa, and Indiana. The peculiar little twisted brachiopod *Streptis,* of Europe, also occurs at Batesville, Ark., as do the peculiar trilobites *Deiphon* and *Staurocephalus,* which occur also at Chicago. The notable case of the square-topped operculated coral has already been mentioned. The presence of these several very peculiar and specialized forms at these localities on the two continents, taken in connection with the many less peculiar forms, clearly implies free intermigration and points with probability to the northern route.

The faunas that occupied the Appalachian trough, the St. Lawrence embayment, and the Atlantic coast appear to have had only indirect and limited connection with that of the interior during the earlier and Mid-Silurian epochs.[1] In the present state of knowledge, these bear the aspect of provincialism, as they have only a few species common to the great cosmopolitan fauna of north central America and northern Europe.

The Closing Restrictional Stage.

Following the luxuriant life of the Mid-Silurian epoch, there came, in North America at least, a very notable decline due to the withdrawal of the epicontinental waters from the larger part of the interior and to the conversion of the remainder into an excessively salt sea. In the deposits (Salina) of this sea almost no fossils are found The tract of excessively briny water appears to have formed a veritable " dead sea," though it was perhaps not absolutely devoid of life. This almost lifeless sea was a peculiar and rather local development, and is to be regarded as a striking incident only in the more general restrictional movement. In addition to this special feature, the life evolution appears to have been affected by the partial replacement of the marine fauna by a fresh or brackish-water fauna, another unusual feature, at least one not before clearly recorded. It cannot be said, however, that this was certainly true, but it appears to us the better of the two interpretations that will presently be set forth. If this be correct, the rich marine fauna which prevailed so widely in the Mid-Silurian times suffered restriction in the closing Silurian stages not only to the

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[1] Ulrich & Schuchert, Rep. N. Y. St. Pal., 1901, pp. 647–651. Weller, Geol Surv. N. J Pal., Vol. III, 1901, pp. 72–76.

tent of the increase of the land area, but also to the extent that se
ıter was replaced by water bodies too salt or too fresh for the strict
ırine life.

The importance of recognizing the fresh-water or brackish-wat
ınas, if they really were such, lies in the fact that they did not coı
tute a relief or a resilience from the restrictional movement of t
ırine fauna, but intensified it. They were a feature of the reciproc
pansional evolution of the land life in the broader sense of th
·m which includes the life of the land waters as well as that of t
ıd itself. The life of the land and land-waters expanded and co
ıcted together in general, and in a phase opposite to that of the se
ıe fauna which brings up this interesting question is that of the Wat
ıe to which we now turn.

The advent of a remarkable crustacean fauna.—The Waterlir
ds represent a gradual return of the Salina basin to a condition h
;able to life. The fauna contained in these beds is limited, but mc
;eresting and suggestive. In its dominant aspect it was a radi
parture from that of Mid-Silurian stage, in that most of the famili
ırine types were absent, while its signal feature was an abundar
large crustaceans of types barely represented before. The mc
aracteristic of these were the great *Eurypterus* (Fig. 189, *a*) and t
ll more gigantic *Pterygotus* (Fig. 189, *b*). The former reached
ıgth of one and a half feet or more, and the latter attained in t
xt period (Devonian), to which this stage was a transition, a leng
over six feet. For crustaceans, these were truly gigantic dime
ıns, and were probably never surpassed. These giants among th
ıd seem clearly to have been aquatic forms, but whether they we
imarily marine or fresh-water habitants is not so obvious. Th
e wholly extinct, and their habitat can only be inferred from th
sociations. Some crustacean fragments that seem to belong
e same subclass as the eurypterids (*Merostomata*) have been fou
· Walcott in Pre-Cambrian beds,[1] but their associates are too f
throw much light on this question, though they favor a mari
.bitat. A very few eurypterids appear in the Ordovician, whe
ey are associated with marine invertebrates. In the Waterlin
·ds they are associated with ceratiocarids and ostracodes which a
ıually marine, and, very rarely, with certain brachiopods, whi

[1] Bull. Geol. Soc. Am., Vol. X, pp. 199–224, 1899.

are marine. In the transition beds of England, Sweden, and Russia, the eurypterids are associated more freely with marine forms, but they are also associated with the seeds of land plants and with fish which, in the succeeding stage, seem to have occupied land waters chiefly. In the Devonian and Carboniferous periods, in which the eurypterids reached their climax and passed into their decline, and where they seem to have been in their more normal relations, they are associated with land plants, scorpions, insects, fishes, and fresh-water amphibians, which seem to imply a fresh-water habitat. In the light of these facts the more common inference has been that they were originally marine forms, and became adapted later to brackish and fresh-water conditions.[1] The alternative inference is that they were originally denizens of the land waters, and that their remains were occasionally and sometimes quite freely carried out to sea by streams, and were

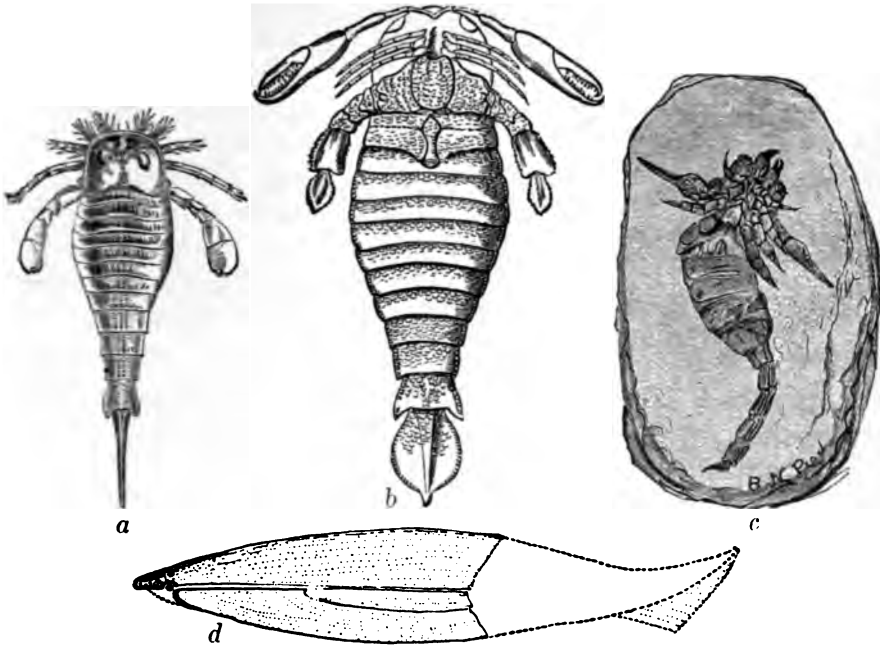

FIG. 189.—*a*, ***Eurypterus fischeri*** Eich., restoration after Schmidt; *b*, ***Pterygotus anglicus*** Agass., restoration after Woodward; *c*, ***Palæophonus caledonicus*** Hunter, after Peach; *d*, ***Palæaspis americana*** Claypole, restoration by Claypole, modified by Dean.

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[1] See Zittel's Text-book of Paleontology, Eastman's Translation, 1900, p. 673.

ıus fossilized with marine forms. Their occasional presence in t
ırlier periods is thus explained, while their seemingly sudden appe
ıce in abundance and in gigantic forms in the closing Silurian, a
ıeir prominence in the land-water deposits of the Devonian and C
ɔniferous finds ready explanation in the fact that these are the fi
ell-preserved fossil-bearing deposits of land waters.[1] In these depos
ıe eurypterids often appear without any marine associates, wh
ccasionally there are some marine or at least brackish-water for
ssociated with them, implying either that they lived in bracki
salt water at times, or that their remains were carried out into su
aters by the land streams or estuarine currents.

These doubts as to the habitat of the eurypterids lend special int
st to their fine development in the Waterlime beds from which m
ısks, crinoids, corals, and similar marine forms are almost entir
ɔsent. The few brachiopods found are usually pauperitic, as thou
ıey lived in uncongenial conditions. The occasional presence of
w undoubted marine forms does not so much indicate that the wat
ere habitually saline as merely that they were occasionally a
ırtially so.

It is suggestive, in this connection, to note that these great crust
ans, appearing thus abruptly in the Waterlime deposits, are n
und in the true marine beds that overlie the Waterlime, as mig
expected if they were true marine types recently come into t
as, or into fossilizable form. It seems, therefore, rather more r
nable to regard their normal habitat as connected with the spec
nditions that prevailed during the Waterlime formation, than wi
e typical conditions of the sea. The Waterlime formation is u
ersally regarded as representing a stage of emergence from the exc
vely salt Salina stage. Emergence from this stage might take eith
f two forms—(1) The connection of the basin with the sea mig
ave become more ample, and the excessive saltiness of the water mig
e reduced by interchanging currents to the normal salinity of t
a. In this case the marine life should creep back into the region
roportion to its endurance of briny water, and the fauna should alwa
e truly marine. (2) On the other hand, without any material chan
the attitude of the surface or in its connections with the sea, t

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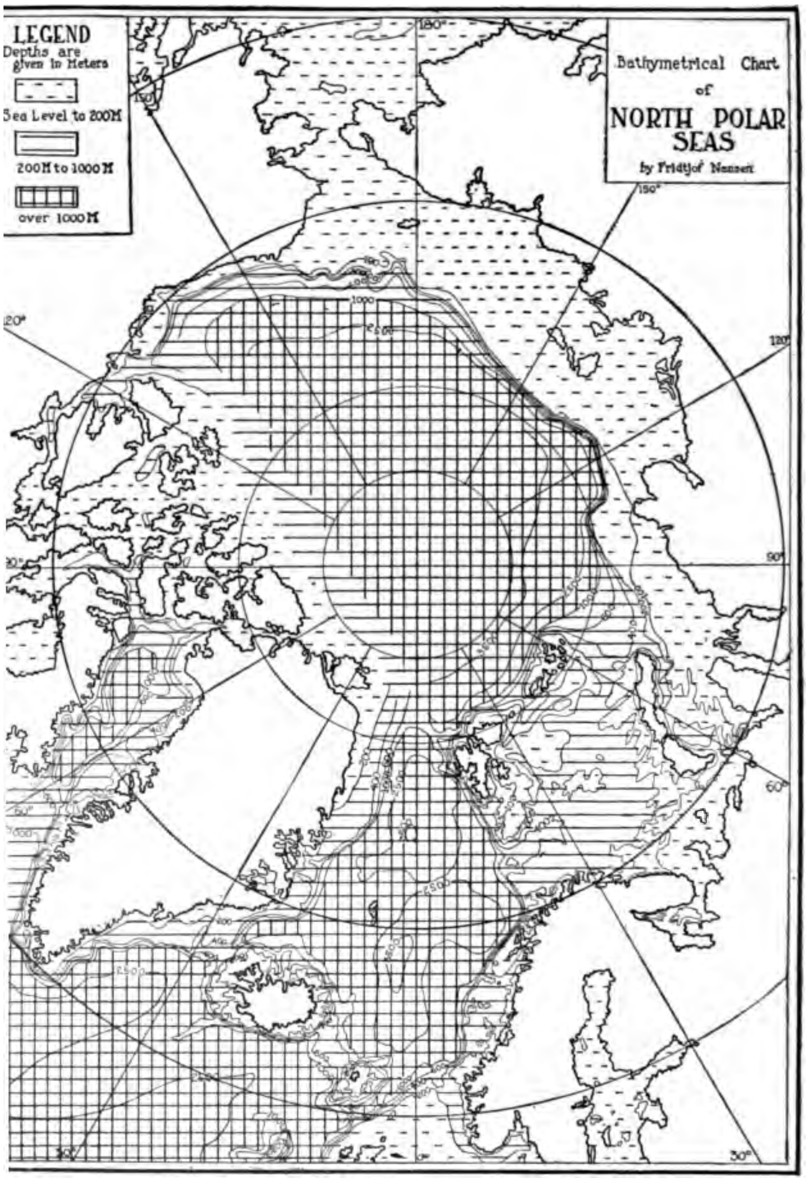
[1] On the Habitat of the Early Vertebrates, T. C. Chamberlin, Jour. Geol., Vol. VI
00, pp. 400–412.

precipitation might be increased, or the evaporation lessened, or both, and as a result, the waters of the basin would become brackish and even quite fresh, where joined by streams, and would thus permit the introduction of a fresh-water fauna from the adjacent land waters. If, at the same time, the limited and perhaps intermittent connection with the sea still obtained, as it appears to have done during the Salina stage, there would also be some opportunity for the introduction of marine forms from the sea, especially at and near the points of such connection. The variations in the ratio of precipitation to evaporation might naturally lead to variations in the constitution of the water of the basin, and hence to conditions favorable to variation in the faunas, and to the mixing of those marine and fresh-water species that could stand the greatest variation in salinity. This latter interpretation is dynamically the simpler and seems to us the better to fit the fossil evidence.

Eurypterids appeared prominently about this time in the faunas of certain beds in England, Wales, Scotland, Sweden, and Russia. In these regions there is no association with salt deposits, a fact which seems to imply that high salinity, as such, was not an essential condition. There, as in America, the eurypterids do not pass up into such of the overlying beds as are well stocked with marine fossils, although there is more or less association with certain marine forms. On the contrary, they seem to pass up into deposits of the "Old Red Sandstone" type, whose other fossils are chiefly land plants and fishes. In the Coal Measures of both continents similar eurypterids are found ossilized with numerous delicate ferns, as though they had been buried ogether in some quiet body of inland water. While these associaions are not entirely decisive, they lend some notable strength to the nference that these large crustaceans were fresh- or brackish-water orms rather than true marine forms, and to the further inference that he peculiarities of the fauna of which they are a conspicuous factor were dependent upon the conditions of terrestrial or semi-terrestrial waters, rather than upon those of true sea-waters.

The appearance of scorpions.—It is at this time also that the earliest known scorpions appeared both in America (New York) and Europe Scotland and Sweden). These were allied to the eurypterids, and heir association lends something of force perhaps to the preceding onsiderations. The European forms have been thought to show



. 190.—Bathymetric chart of the north polar seas, suggesting routes of migratio for marine organisms. (After Nansen.)

breathing pores, and hence to be land species, as are the present forms, but this has been questioned. The sting and the poison glands have been identified, and the significant name *Palæophonus*, " ancient murderer," applied in consequence (Fig. 189, *c*). Whitfield, however, thinks that the American species may have been aquatic.

The presence of fishes.—The addition of fishes emphasizes the peculiarities of this fauna. Except for their singular occurrence in Colorado in the Ordovician, fish remains have not been found in America until this stage. *Palæaspis americana* (Fig. 189, *d*), a low fish-like form referred to the ostracoderms, has been described by Claypole from Pennsylvania. In Europe a few fishes appear somewhat earlier than this in the Ludlow formation, but nearly all the fish remains of the period occur in the very highest horizons regarded as Silurian, or in the deposits that form the transition to the Devonian period, where they are associated with eurypterids and land plants, as well as marine invertebrates. It would appear from the remains that fishes were rather abundant and varied in their development at certain stages. The relics, however, are fragmental and embrace teeth, dermal plates, spines, shagreen scales, etc. These fishes appear to have been the forerunners of the abundant fishes of the Old Red Sandstone (Devonian) into which the transition beds of Great Britain graduate, and as these Old Red Sandstone beds were probably land-water deposits, the association of the fish with the eurypterids and with land plants carries some further presumption that the peculiar crustacean fauna lived normally in land waters. It is not to be overlooked, however, that in the transition beds the fishes are also associated with marine fossils, and there is no question that, before the close of the Devonian period, certain fishes at least became truly marine. It is therefore entirely consistent with either view of the place of origin of fishes to regard these as marine forms, or as forms frequenting both salt and fresh water. It is to be noted further that not a few of the forms conveniently referred to here as fishes were probably ostracoderms which have certain arthropod characters and are not unlikely to be made a separate class, as will appear later.

CHAPTER VIII.

THE DEVONIAN PERIOD.

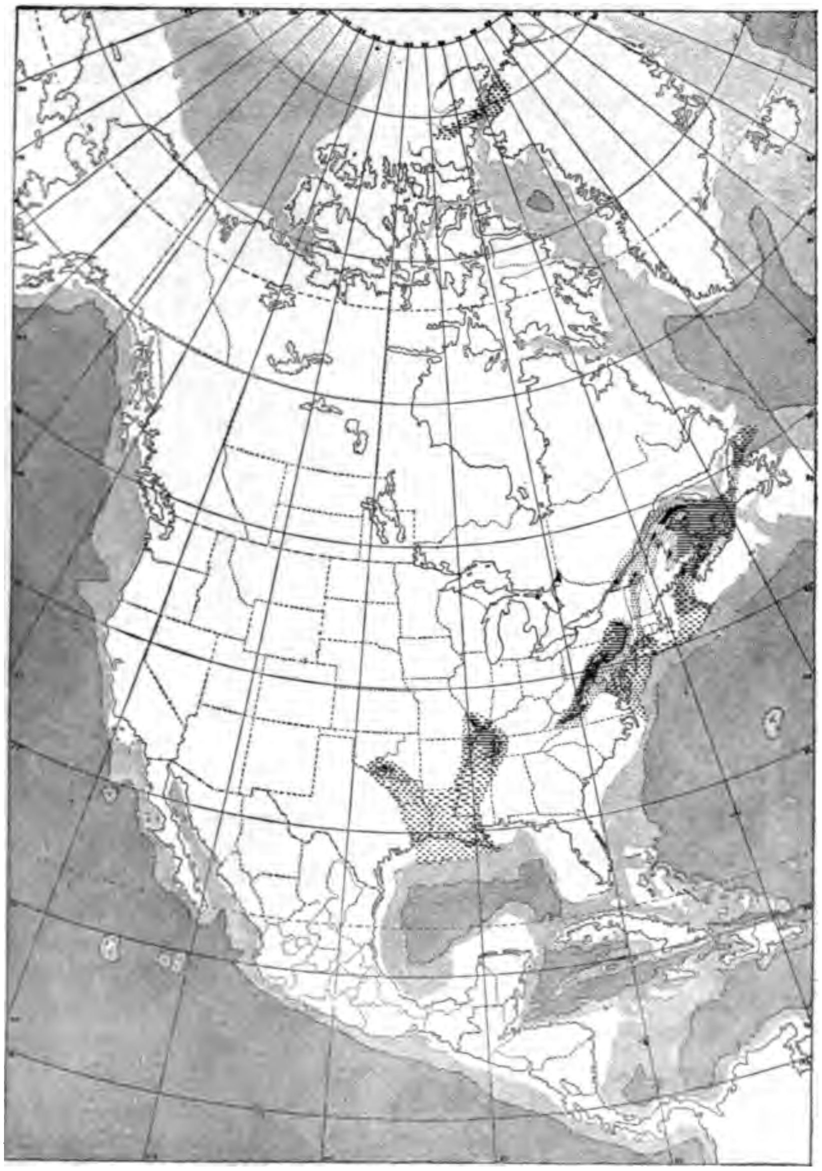
FORMATIONS AND PHYSICAL HISTORY.

THE division plane between the Silurian and Devonian systems is clearly marked than that between the Silurian and the Ordovician. already indicated, there is difference of opinion as to whether the derberg[1] formation belongs to the one system or to the other. Whatever the final reference of the Helderberg formation, its relas to the immediately preceding and succeeding formations serve show that the separation of the Devonian from the Silurian is less inct than that of the Silurian from the Ordovician. Under either these points of view, the sea again invaded the land early in the onian period, perhaps establishing some such relations as shown Fig. 191. During the period, there were changes in the relations land and water, some of which were of great importance in thei cts on the life of the period. These will be noted later.

The subdivisions of the Devonian which have been commonly gnized in America (the Helderberg being included) are as follows several formations being numbered in chronological (and strati phical) order:

5. Chemung-Catskill:
    - Chemung.
    - Portage.
4. Hamilton:
    - Hamilton.
    - Marcellus.
3. Corniferous:
    - Corniferous.
    - Schoharie and Cauda Galli.
2. Oriskany.
1. Helderberg.

As originally classified, there was a *Lower* and an *Upper* Helderberg formatio latter is now more commonly known as the *Onondagan* (Corniferous). In thi me the term Helderberg is applied to the former only. The adjective "lower' efore becomes superfluous.



G. 191.—Map of North America, showing the outcrops of the Helderberg formation and the relations of land and water during the Helderberg epoch. The conventions are the same as in the earlier maps of the series.

The recently revised classification for New York [1] is as follows:

onic...	**Neodevonic....**	**Chautauquan..**	**Chemung (including Catskill)**
		Senecan.......	**Portage beds** **Genesee shale** **Tully limestone**
	Mesodevonic...	**Erian.........**	**Hamilton shale** **Marcellus shale**
		Ulsterian......	**Onondaga (Corniferous) limestone** **Schoharie grit** **Esopus grit**
	Paleodevonic...	**Oriskanian.....**	**Oriskany beds**
		Helderbergian..	**Kingston beds** **Becraft limestone** **New Scotland beds** **Coeymans limestone**

The new classification has an advantage over the old in that tl
ıe name is not used to indicate subdivisions of different importanc
the disadvantage of adding to the burden of nomenclatur
term Devonian will be retained instead of Devonic, and Lowe
ldle, and Upper Devonian, as synonyms for Paleo-, Meso-, and Ne
onic, respectively. The subdivisions in the last two colum
to be regarded as appropriate for the New York region, and tho
he second columns from the right may have wider applicability.
Recently revised classifications for Maryland [2] and the interio
given below. In the latter, Helderberg is excluded.

Maryland.	Interior.
. Hampshire = Catskill in part.	5. Chemung.
. Jennings = Genesee and Portage.	4. Portage (including Genesee).
. Romney = Erian.[4]	3. Hamilton.
. Oriskany.	2. Onondaga (Corniferous).
. Helderberg = Coeymans.	1. Oriskany.

THE LOWER DEVONIAN.

The **Helderbergian series.**—The known Helderbergian series
ely confined to the eastern part of North America. It is known (
Maine [5] and, beyond the United States, in Gaspé, New Brunswic

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[1] Clark and Schuchert, Science, Vol. X, 1899.

[2] O'Hara, Maryland Survey, Allegany County.

[3] Hayes and Ulrich, Columbia (Tenn.) folio, 1903.

[4] Prosser, Jour. of Geol., Vol. XII, p. 361.

[5] Williams, Bull. 165, U. S. Geol. Surv.

and Nova Scotia, and a remnant belonging to the same general province occurs near Montreal;[1] (2) in the Appalachian belt, and (3) in the lower Mississippi basin (see Fig. 191).

During the Helderbergian epoch, as before, the sea of the Appalachian trough seems to have had eastward, but not westward, connections. The fauna of the Appalachian Helderbergian beds is very similar to that of the region east of the lower St. Lawrence. From these relations it is inferred that the Helderbergian fauna of the eastern coast, like the Silurian fauna of the same region, found entrance to the Appalachian trough, and from relations which will not be detailed here, it is conjectured that the entrance was effected by an inlet near the present Chesapeake bay (Fig. 191). The fauna of the Helderbergian beds in the lower Mississippi basin is also of the Appalachian type, indicating geographic conditions which allowed of the migration of the Atlantic-coast faunas into this region.

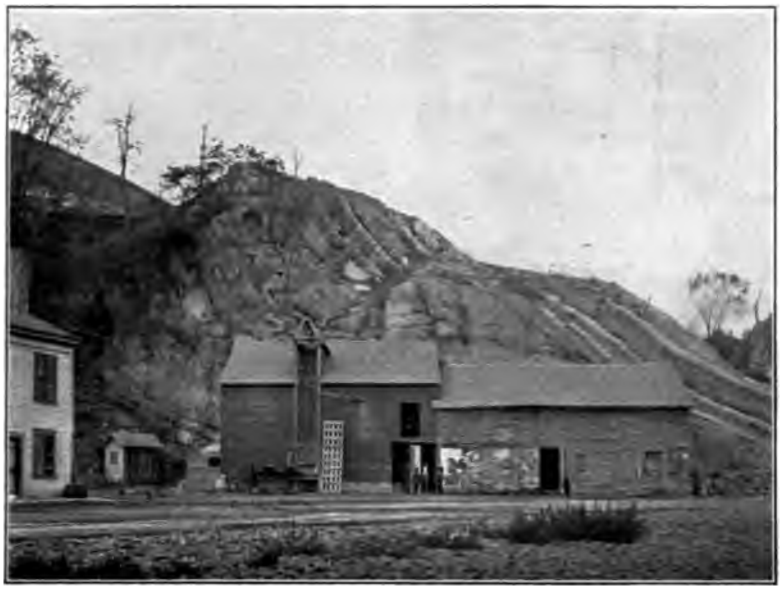

FIG. 192.—Helderberg limestone, Wilbur, New York. (Darton, U. S. Geol. Surv.)

The Helderberg formation is largely limestone, which suggests subaërial erosion was not taking place at a rapid rate, and that principal formation of the epoch, as far as our continental area ncerned, was extracted from the sea-water.

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[1] Whiteaves, Am. Geol., Vol. 24, 1899. pp. 210–40. A review of the Devonian of Canada.

The Helderbergian series is 300 to 400 feet thick in eastern New k, and 350 to 600 feet in Pennsylvania. It thins to the west, g but a few feet thick in Ohio, and 100 feet or less in western Ten-ee. In the vicinity of Gaspé, there is a continuous formation imestone some 2000 feet thick, a part of which is of Helderbergian

The Oriskany.—The Oriskany formation is best known in the alachian region, but beds of the same age have a wide but undeter-ed distribution in the eastern part of the Mississippi basin, and he St. Lawrence basin in the southern part of Ontario. Beds con-poraneous with the eastern Oriskany are more widespread than eastern Helderberg formation. In the region where best known, Oriskany is made up chiefly of coarse-grained sandstone. The nity of Cumberland, Md., may be regarded as the center of Oriskany of the mountain belt. From this locality, it extends northeast and southwest, but thins in both directions and loses most distinctive faunal characteristics. To the westward, the al characteristics of the Appalachian belt are found as far as uga in Ontario, indicating that the barrier between the Ap-chian trough and the interior—a barrier which seems to have effective since the Utica epoch—was removed during this h, allowing the life of the former region to migrate into the latter. the southerly part of the Mississippi basin (western Tennessee) Oriskany fauna also appears, though the formation in which it rs (Camden chert) has no lithological likeness to the Oriskany he east. In general, the beds of the interior, which are perhaps temporaneous with the Oriskany of the Appalachian belt, are not ply differentiated from the overlying beds, either lithologically aleontologically.

As developed in the Appalachian belt, the Oriskany is a thin forma-, ranging from a score of feet in New York to several hundred feet aryland and Virginia.

In the northeast (Gaspé, New Brunswick, and Nova Scotia) the derberg formation has not been clearly differentiated from over-g parts of the Devonian system, but beds containing the Oriskany fauna have here an extensive development. In northern Maine (Moosehead Lake region) the Lower Devonian series (probably with other undifferentiated beds) is reported to have a thickness of several thousand feet.[1] From the testimony of fossils, both European and American, it is supposed that there was shallow-water connection between eastern North America and southern Europe, allowing marine life not at home in deep water to pass from the one continental region to the other.

THE MIDDLE DEVONIAN.

Local eastern formations.—In the east the Oriskany formation is succeeded by other clastic beds (Esopus, formerly called Cauda Galli, and Schoharie grits). Their equivalents have not been differentiated west of the Appalachian region. These formations are relatively thin, and are made up of sediments accumulated near shore.

The Onondaga.—They are succeeded by the Onondaga limestone, which is much more widely distributed, spreading from New York on the east to the Mississippi. Within this area, the Onondaga rests, now on Silurian[2] (Niagaran or later) beds, and now on Waterlime,[3] often with little evidence of unconformity, and with no intervening beds which carry an Oriskany fauna.

During the Onondagan epoch, the connection between the Atlantic and the interior by way of the Chesapeake region appears to have been closed (Fig. 193): but the descendants of the Oriskany fauna which had entered the Mississippi basin while the passage was open, are to be recognized in the fauna of the Onondaga limestone.

The lower beds of the Onondaga limestone may have been in process of deposition over the eastern interior while the Esopus beds were accumulating in the Appalachian belt. If this be the case the conditions for limestone accumulation were presently extended eastward

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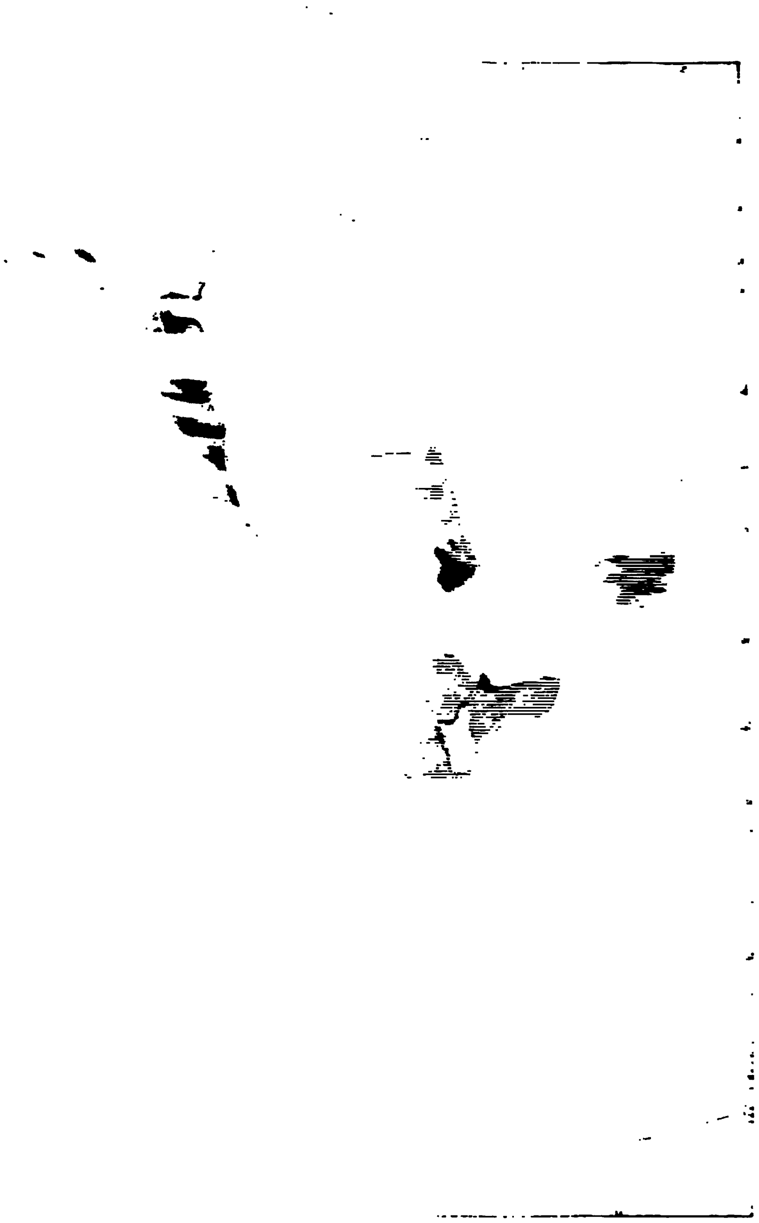
[1] Williams and Gregory, Bull. 165, U. S. Geol. Surv., p. 22.

[2] Geol. Surv. of Iowa, Norton, Vol. IV, p. 127, and Calvin, Vol. VII, p. 54. See also Simonds, Arkansas Geol. Surv., Vol. IV, 1888; Hopkins, Vol. IV, 1890; Vol. II, 1891; Williams (H. S.), Vol. V, 1892. The presence of Middle Devonian strata in Arkansas is uncertain.

[3] Blatchley and Ashley, 22d Ann. Rept. Dept. of Geol., etc., of Indiana; and Sherzer, Geol. Surv. of Michigan, Vol. VII, p. 37; so also in Missouri, see Missouri Geol. Surv., Vol. XII, p. 67, and 22d Ann. Rept. U. S. Geol. Surv., Pt. II, p. 85; and Shepard, Missouri Geol. Surv., Vol. XII, pp. 67–82.



[illegible] formation
[illegible]

The Onondaga limestone of the interior, often described und)ther names (Corniferous,[1] etc.) is usually not thick, rarely more th l00 or 200 feet, but it nevertheless represents a long interval of tin since limestone accumulates but slowly.

Onondaga limestone (or the equivalent of the Ulsterian seri)ccurs east of the Appalachian belt in northern New England a Canada where it has a distribution similar to that of the Helderbe

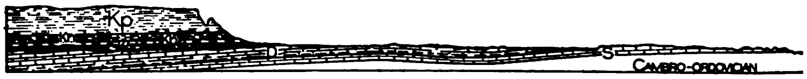


FIG. 194.—Section showing the relations of the Devonian system between Porcu Mountain and the mouth of the Saskatchewan River. Length of section, ab 125 miles. (Tyrrell, Geol. Surv. of Canada.)

At Gaspé, 800 feet of limestone, overlain by 1000 feet of sandsto have been referred to the epoch. Though these beds may be time-equivalent of the Onondaga of the interior, they do not cont the fauna characteristic of the formations of the interior, and tl exact correlation is open to question.

The equivalents of the Onondaga beds, or of other subdivisi of the Middle Devonian of the east, have not been differentiated the western part of the United States, nor in the great northwest te tory of Canada, though the Devonian system is represented in b these great areas.

The map (Fig. 193) showing the outcrops of the Onondaga se represents an extensive outcrop in the northwestern part of the (tinent. This representation expresses the belief that the Devo of this region includes the equivalent of the Onondagan. It proba includes also the later parts of the system. No Devonian formati are known to underlie the Great Plains of the United States.

The Hamilton or Erian series.—After a considerable period, du which there were relatively clear seas over the northeastern inte conditions changed so as to give origin to deposits of mud where the Onondaga limestone had been accumulating. These mud beds and their equivalents, now consolidated, constitute the Marcellus and Hamilton formations of New York (see Fig. 195). West of Ohio and east of the Mississippi the equivalents of the two formations are commonly grouped together under the name Hamilton, or given local names (see Appendix, Vol. III). Shale is the most common rock at the east, but with it is associated not a little limestone, and in the west, limestone predominated. Southward, in Kentucky and Tennessee, the equivalent formations, where present,[1] consist largely of black shale and slate.

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[1] The name *Corniferous* was originally given to the Onondaga formation cause of the local (New York) abundance of chert nodules which stand out (h like) when the limestone is weathered. These nodules are sometimes a or more in diameter, and often contain abundant shells of microscopic pl (diatoms, etc.), spicules of sponges, and teeth of annelids. Chert nodules however, hardly more characteristic of this formation than of many otl and the name is therefore an unfortunate one, and is gradually being set asid

These changes in sedimentation appear to have been accompanied by changes in geography (compare Figs. 195 and 193). During the early part of the Marcellus epoch, the connection between the Atlantic and the interior by way of the Chesapeake may have been re-established.[2] At about the same time, too, considerable areas in the southern and n the northwestern parts of the Mississippi basin appear to have been ubmerged. In the Mississippi basin, the Hamilton formation probably overlaps its predecessor, resting on Silurian and perhaps even n Ordovician beds. The same relations hold in the southern Appaachians, where Devonian beds, probably the equivalents of the Marellus and Hamilton, overlie Silurian and Ordovician unconformably. The submergence of the land in the south appears to have been sufficient to cause the sea to overspread areas which had been land since he close of the Ordovician (southern Appalachians and areas farther west) and perhaps to open up a connection between the interior sea nd the Gulf of Mexico, allowing shallow-water species of animals to migrate into the Mississippi basin from the south, perhaps from South America (see Hamilton fauna, p. 460). The Cincinnati arch and the orresponding Nashville dome may have been land (islands or a peninula, Fig. 195) throughout the Hamilton epoch, though this cannot e affirmed. If the Hamilton formation once overspread them, it as been removed by erosion. The map, Fig. 195, shows the general elations of the series, and at the same time suggests the geography f the epoch.

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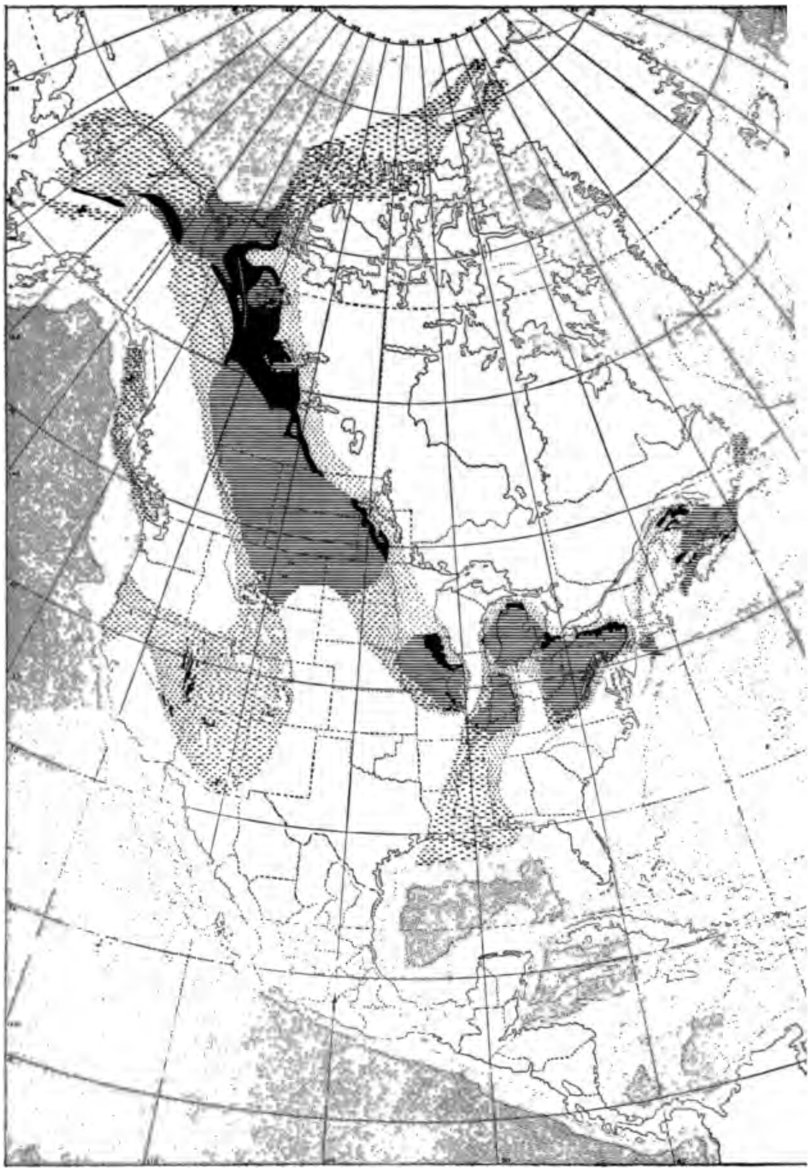
[1] Hayes and Ulrich, Columbia (Tenn.) folio, U. S. Geol. Surv. This folio gives late correlation table for the Ohio-Kentucky-Tennessee region.

[2] Ulrich and Schuchert, Bull 52 (Paleontology 6) New York State Museum, Report the State Paleontologist, 1902, p. 654.



IG. 195.—Map of North America showing the outcrops of the Hamilton forma
and the relations of land and water during the Hamilton epoch. The b
area at the north probably includes Lower and Upper Devonian as well as Mi
Compare Figs. 193 and 196. The conventions are the same as in earlier maps.

The conditions for the origin of the Hamilton shales would seem to be met if the surrounding lands (Appalachia and lands north of the interior sea), low and protected while the Onondaga limestone was making, were more elevated or less protected by vegetation, or subjected to more concentrated or spasmodic precipitation. Under the former conditions, the land formations would have been undergoing decay, but the products of the decay might not have been removed; under the latter, there would have been opportunity for the transportation of the products of decay. Even during the general period of shale formation, however, limestone (often shaly) was making in many places. This was especially true in the Mississippi basin, so that while the term "Hamilton shales" is in common use, "Hamilton shales and limestones" would describe more accurately the Erian series of this region. The Marcellus shale is locally more or less bituminous, indicating the presence of abundant plant life in the seas in which it was deposited.

In the east, the Hamilton (including Marcellus) formation is very thick, being 1500 to 5000 feet thick in Pennsylvania, where it is mainly of fragmental origin. Its thickness over the interior, where it contains more limestone, is but a fraction of this amount.

Middle Devonian in the northwest.—A considerable area of Devonian which has sometimes been called Hamilton is found in the basin of the Mackenzie river and southward to Manitoba.[1] The great arm of the sea in which the Devonian of this area accumulated appears to have extended as far south as northern Missouri (Fig. 195). Whether this arm of the sea antedated the Hamilton epoch is uncertain. Devonian beds, some of which may be the equivalent of the Hamilton, also outcrop along the main ridge of the Canadian Rockies.

The fossils of this northwestern Devonian do not correspond with those of the Hamilton formation of the east (Illinois to New York), and if the beds of the two regions were contemporaneous, as they may have been, they seem to have been deposited in waters which were not connected. The union was probably prevented by a narrow belt of land running south-southwest from Wisconsin to Missouri, somewhat as shown in Fig. 195. Till late in the Hamilton, this land seems to have constituted a barrier between the eastern interior sea, and a northwestern sea which stretched from Missouri on the sout through the Mackenzie basin, to the Arctic Ocean on the Toward the end of the Hamilton epoch, this barrier seems to been removed sufficiently to allow the waters and the life on op sides to mingle freely. The removal may not have affected the of the barrier, but it seems to have been sufficient to accomplis results indicated.

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[1] For review of the Devonian of Canada, see Whiteaves, Am. Geol., Vol. XXIV, 1899, pp. 210–40.

Belief in the barrier and in its removal is based primarily on ontological evidence to be sketched later, but it may here be that up to the end of the Hamilton, the fauna to the west of th posed barrier was unlike that to the east, while during the succeeding epoch the fauna on the northwest seems to have in the eastern interior sea.[1]

The northeastern region.—Rocks (sandstone) of Middle Dev age, presumably Hamilton, are known to occur in the eastern (Gaspé), where some of them appear to be of fresh-water origin. evidence of this origin is found in the abundant land-plant f Some portions of these beds are probably the time-equivalents Hamilton of the interior, but their exact equivalency has not established.

Geographic changes during the Middle Devonian.—The dis tion of the Hamilton beds indicates several changes in the geog of the continent, as compared with that of early Devonian time. were (1) a slight elevation (relative) to the east, interrupting time the connections between the sea of the Appalachian area the Atlantic; (2) a subsidence to the southward in the interior, merging areas which had long been land, and perhaps conne the interior sea with more southerly waters; and toward the cl the epoch, (3) the removal of the barrier which separated the n western interior sea from the eastern. This last change may pe be looked upon as marking the closing stage of the Hamilton epo

THE UPPER DEVONIAN.

The Upper Devonian series has a distribution (Fig. 196) si to that of the Middle Devonian, though it is perhaps less widesp

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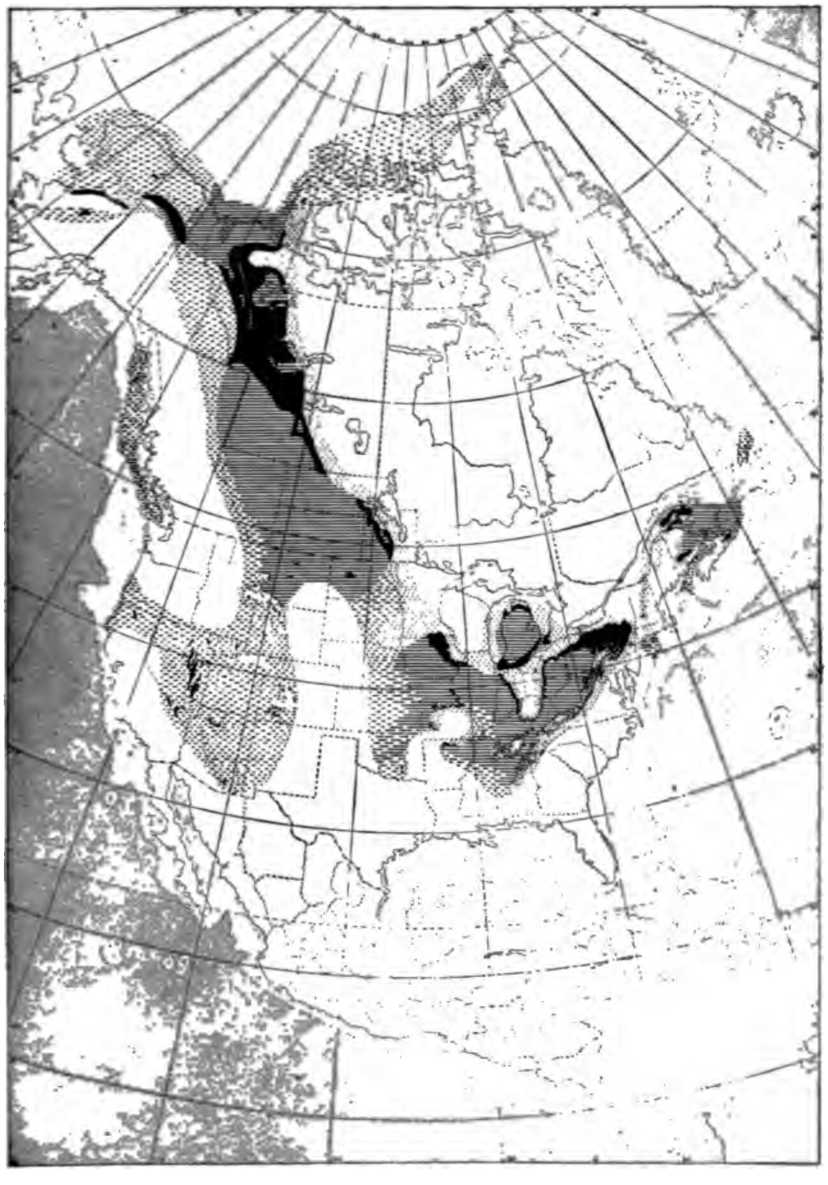
[1] The Hamilton fish fauna of Wisconsin, Illinois, and Iowa is thought by Eas to have been related to the Onondagan fish fauna of New York. Bull. Geol Am., Vol. XIII, p. 537.



IG. 196. - Map of North America, showing the outcrops of the Upper Devonian formations, and the relations of land and water in late Devonian time. The conventions are the same as in earlier maps (see p. 220). (See note under Fig. 195.)

to the south, on the whole, although in southwestern Missouri, U Devonian beds appear to be present where the older parts of system are not known,[1] and the same relations appear to hol northern Arkansas. In some parts of Iowa, the Upper Devo is unconformable on the Middle (Fig. 197), but the separation of

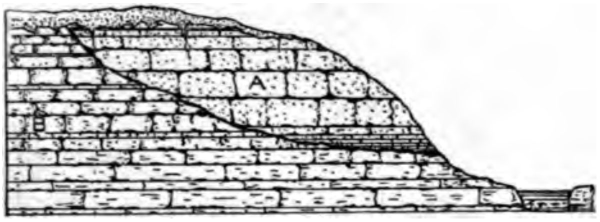


FIG. 197.—Hypothetical section showing the probable relations of the Upper (Quarry) and Middle (Cedar Valley) Devonian, Penn Township, Johnson C (Calvin, Ia., Geol. Surv.)

Upper Devonian from the Middle is generally based on faunal r than on stratigraphic grounds, the division being made where distinctive Hamilton fauna gives place to another. The faunal cha which the upper Devonian records, seem to have resulted, in at least, from the immigration of life from the northwestern s the previous epoch into the eastern interior. This immigration place toward the close of the Hamilton epoch, and the inv species probably moved somewhat slowly from west to east, ap ing earlier in Wisconsin than in New York. A connection bet the Atlantic and the interior by the old route during the early of the late Devonian (Portage, see p. 433) has been suggested to ac for certain peculiarities of the Devonian faunas of this stage i east.[2]

The Tully, Genesee, and Portage formations, or Senecan series. the base of the Upper Devonian in New York, there is, locally, a bed of limestone (the *Tully*). At the horizon of this limestone, where it has otherwise run out, there is a discontinuous layer of pyrites, which extends over a considerable part of western New The waters of this region were polluted by some iron compound (ably carbonate). The iron is believed to have been precipitate sulphuretted hydrogen or ammonium sulphide derived from decaying vegetable or animal matter. This layer of pyrites is remarkable for its fauna of dwarfed species, 45 in number. The average size of the species is only about one fifteenth of the normal. Not only are the species dwarfed, but they represent species arrested in their development, appearing like the young of species of earlier Devonian types. The succeeding *Genesee shales* are black and bituminous, and range from a few feet (25 on Lake Erie) to a few hundred feet (150 in central New York, 300 in west central Pennsylvania) in thickness. The *Portage formation*, composed of shales and sandstones, is much thicker, being 1000 to 1400 feet in western New York. To the southward, its separation from the Chemung is less distinct than in New York. All these clastic beds bear evidence of shallow-water origin. Their stratigraphic relations are suggested by Fig. 186.

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[1] Shepard, Mo. Geol. Surv., Vol. 12, p. 65.

[2] Ulrich and Schuchert, op. cit., p. 656.

The Chemung and Catskill formations (Chautauquan series).—The Chemung formation of New York is very like the Portage, though more arenaceous. It is locally conglomeratic, and everywhere bears the marks of a shallow-water origin. Locally the conglomerate has been eroded into fantastic forms, giving rise to "Rock Cities," as near Panama in western New York. The formation ranges in thickness from 950 feet near Lake Erie, to 1500 feet in the vicinity of Cayuga Lake. Much greater thicknesses, 8000 feet maximum, are attained in Pennsylvania, but the formation thins rapidly westward. In northern Pennsylvania, the Cattaraugus formation overlies the Chemung, and a part of the Oswayo formation above the Chemung is also classed as Devonian.[1]

West of New York and Pennsylvania the Upper Devonian beds have few commonly recognized subdivisions, or none at all, and the eastern names are not in general use (see Appendix, Vol. III).

It may be here remarked that the Devonian was probably more extensively developed to the southwest than was formerly supposed. Devonian beds are said to occur at the summit of the Ozark uplift in Missouri,[2] though their present exposure in this region seems to be limited.

In the Catskill region, there is a series of red shales and sandstones which appear to be, in a general way, the time-equivalents of the Che-

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[1] Fuller, Gaines (Pa.) folio, U. S. Geol. Surv.

[2] Keyes, Bull. Geol. Soc. Am., Vol. XIII, pp. 268–292.

ıng. In some places the Catskill beds may represent less than t
l Upper Devonian, and in others more. The Catskill formati
sufficiently different from the rest of the Upper Devonian to in
e that the sediments of which it is composed accumulated unc
ıditions very different from those which obtained farther we
is formation is poor in fossils, and such as occur are partly, if r
olly, of fresh- and brackish-water forms. Hence it is inferred tl
Catskill region was at least so far shut off from the ocean as r
afford the conditions necessary for marine life. The formation
table for its redness, a feature which marks many other formatic
de in inclosed or partially inclosed seas, inland lakes, or basins.

The Catskill formation has a thickness of 3000 feet in New Yc
1 twice that amount farther southwest in Pennsylvania. Lo
ls of sandstone (the Oneonta of central New York), seemingly li
Catskill in origin, occur outside the Catskill region, suggesti
ıt similar conditions now and then existed farther west.

The thickness of the Upper Devonian in central and western N
rk approaches 4000 feet, and it is still thicker in Pennsylvania a
ryland,[1] locally reaching a thickness of 8000 or 9000 feet. In O
same series (Black or Ohio shale [2]) has a maximum thickness
)0 feet, but thins notably to the north and west, being at most o
w hundred, and often but a few score feet thick in Indiana,[3] Illin
va, southern Michigan, Kentucky, and Tennessee.[4] Various nar
applied to the series and its subdivisions in various localities.

West of the Great Plains, the equivalents of the Chemung of
t have not been separated from other parts of the Devonian syste
e Upper Devonian seems also to be represented in Maine and s
ther northeast.[5]

The sections of the Devonian given in the Appendix, Vol. III, g
ne idea of the development of the system in various parts of
ıtinent.[6]

[1] Prosser, Jour. of Geol., Vol. IX, pp. 415–42. This article is a concise summ
he Paleozoic systems of Maryland.

[2] Geol. Surv. of Ohio, 1873–93.

[3] Twenty-second Ann. Rept. Dept. of Geol. and Nat. Res. of Indiana, p. 1

[4] Hayes and Ulrich, Columbia (Tenn.) and Campbell, London (Ky.) folios, U.
ıl. Surv.

[5] Williams and Gregory, Bull. 165, U. S. Geol. Surv., p. 22.

[6] The Devonian of special regions east of the Great Plains is described in the
shown on the maps of the following folios of the U. S. Geol. Surv.:

DEVONIAN OF THE WEST.

The Devonian system, so far as known, is absent from the larger part of the Great Plains within the United States. This great expanse of territory was probably land during the Devonian period. No Devonian beds are found about the older formations in the Black Hills or in the vicinity of Hartville, Wyo., where the succession of formations has been studied in detail. The Helderberg is somewhat developed farther southwest in the Arbuckle Mountains of Indian Territory [1] (Woodford chert, see Appendix, Vol. III). The presence of Devonian beds in Texas is also uncertain, though Helderbergian beds at least probably occur in the southwestern part of that State.[2] The Devonian system has little development in the Rocky Mountains, but is somewhat widespread between the Rockies and the Sierras. It is represented in Arizona (Fig. 240),[3] Colorado,[4] Utah,[5] Nevada,[6] Wyoming (Fig. 247), and Montana,[7] and the Canadian Rockies.[8] Though its outcrops are not extensive, its actual area is obviously much greater. In some places, as about Globe, Arizona, the system is much faulted and affected by igneous

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bama. Stevenson, Gadsden; *Georgia*, Rome, Ringgold; *Kentucky*. Loudon, Richmond; *Kentucky–Virginia–Tennessee*, Estillville; *Pennsylvania*, Brownsville, Connellsville, Elkland-Tioga; *Pennsylvania–New York*, Gaines; *Tennessee*, Briceville, Chattanooga, Cleveland, Columbia, Kingston, Loudon, Maynardville, McMinnville, Morristown, Sewanee, and Standing Stone; *Tennessee–North Carolina*, Knoxville; *Virginia–Tennessee*, Bristol; *Virginia–West Virginia*, Monterey, Pocahontas, Staunton, Tazewell; *West Virginia–Virginia*, Franklin, Piedmont; *West Virginia*, Buckhannon.

Details concerning the system are also found in the geological reports of the several States where the system appears at the surface.

[1] Taff, Atoka (I. T.) folio, U. S. Geol. Surv.

[2] Hill, Physical Geography of the Texas Region, folio 3, topographic atlas, U. S. Geol. Surv., p. 4.

[3] Blake, Jour. Geol., Vol. IX, 1901, p. 68; and Am. Geol., Vol. XXVII, 1901 p. 164; Walcott, Am. Jour. Sci., Vol. XX, 1880, p. 221; and p. 436.

[4] Spencer, Am. Jour. Sci., Vol. IX, 1900, p. 125; Spurr, Mono. XXXI, U. S. Geol. Surv., pp. 9–30; Girty, Professional Paper, No. 16, U. S. Geol. Surv., pp. 156–162.

[5] King, Geol. Expl. of the 40th Parallel, Vol. I; see also Weller, Jour. Geol., Vol. X, pp. 423–32.

[6] Knight, Bull. 45, Wyo. Exp. Station; Yellowstone and Absaroka folios, U. S. Geol. Surv.; Spurr, Bull. 208, U. S. Geol. Surv.

[7] Little Belt, Fort Benton, Livingston, and Three Forks, Mont., folios, U. S. Geol. Surv.

[8] Dawson, Bull. Geol. Soc. Am., Vol. XII, p. 68, and Ann. Rept. Geol. Surv. of Canada, Vol. II, p. 19D.

ck;[1] in others it is bounded by unconformities, both below anc ove,[2] while in still others its limits are not sharply defined. Ii is western interior the system has not been generally subdivided d where subdivisions have been made, they have not been cor lated with those of the east. In the Great Basin region, Onondagai orniferous) types of fossils, and in overlying beds types correspond g to the Eurasian (rather than to the east American) faunas of th rthwest, have been recognized. Hamilton types, with great vei al range also occur. The testimony of the fossils of the Basin regio to the effect that it was not connected either with the eastern interio a or with South America in such a way as to allow of the free inter igration of marine life.

The system is 8000 feet (6000 feet of limestone and 2000 feet c ale) thick in the Eureka district of Nevada,[3] and 2400 feet (quartzit d limestone) in the Wasatch Mountains. In some parts of th est, as in the Yellowstone Park, the system is thin (160 feet[4]), an t divisible on physical grounds into distinct formations. In th estern interior generally, limestone is the dominating formation.

Still farther west, on the Pacific side of the Paleozoic land are evonian is known in both northern[5] and southern[6] California, ar ay be represented in many places where the rocks are metamo iosed past identification. In the Klamath mountains, the Devoni hiefly Middle) is much disturbed, and contains igneous rocks (tu d flows). The Devonian faunas of the coastal region, like tho the Great basin, are Eurasian in their affinities.

The Devonian system is also abundantly represented in wide parated parts of Alaska.[7]

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[1] Ransome, Professional Paper, No. 12, and Bisbee folio, U. S. Geol. Surv., pp. 39–4 so Reagan, Am. Geol., Vol. 32, p. 278.

[2] Am. Jour. Sci., Vol. XXVI, pp. 437–438, 1883.

[3] Geol. Expl. of the 40th Parallel, Vol. I; see also Weller, Jour. Geol., Vol. . 423–32.

[4] Weed, Yellowstone Nat Park folio, U. S. Geol. Surv.

[5] Diller, Am. Jour. Sci., Vol. 15, 1902, p. 344.

[6] Spurr, Bull. 208, U. S. Geol. Surv.

[7] Brooks, Bull. Geol. Soc. Am., Vol. XIII, pp. 256–61, and Professional Pap o. 1, U. S. Geol. Surv., p. 211; Schrader, Bull. Geol. Soc. Am., Vol. XIII, p. 24 d Professional Paper, No. 20, U. S. Geol. Surv., pp. 62–67.

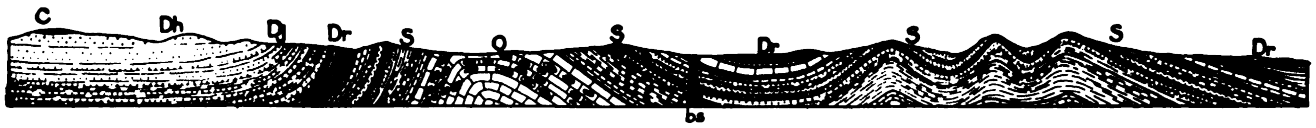


FIG. 198.—Section showing the relations of the Devonian in the Appalachians of Virginia and West Virginia. The section of the folio is modified to the extent of introducing a dike, *bs*. Dikes occur not far away, though not in this section. *O*=Ordovician; *S*=Silurian; *Dr* (Romney shale). *Dj* (Jennings formation), and *Dh* (Hampshire formation)=Devonian; *C*=Carboniferous. Length of section, about 14 miles. (Darton, Monterey folio, U. S. Geol. Surv.)

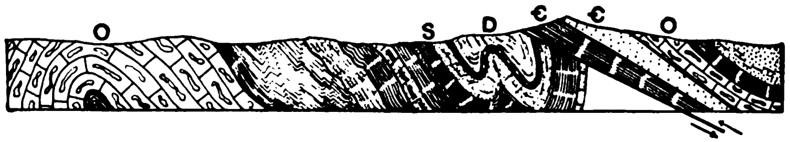


FIG. 199.—Section showing the Devonian in the region of Knoxville, Tenn. *€*=Cambrian; *O*=Ordovician; *S*=Silurian, and *D*=Devonian. Length of section, about 5 miles. (Keith, U. S. Geol. Surv.)

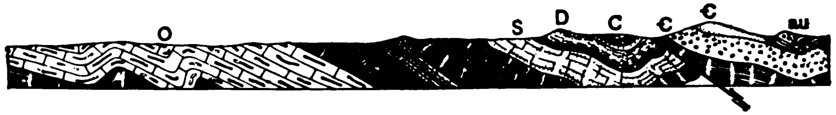
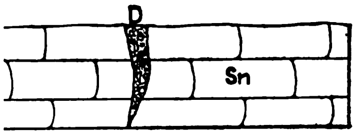


FIG. 200.—Section showing the relations of the Devonian and other Paleozoic systems in the vicinity of Loudon, Tenn. *€*=Cambrian; *O*=Ordovician; *S*=Silurian; *D*=Devonian; *au*=age unknown. Length of section, about 7 miles. (Keith, U. S. Geol. Surv.)

Areas Where the Devonian Comes to the Surface.

While the Devonian system is widely distributed it does not appea the surface over large areas. Obviously in the beginning the vonian formations were as wide-spread as the Devonian seas; but e most of the area of North America covered by the Devonian s was also covered by the seas of later periods, the Devonian system s mostly buried. Subsequent withdrawals of the sea and warpings he surface have allowed the overlying formations to be worn away, osing the Devonian at many points, though in the aggregate the as of exposed Devonian constitute but a small fraction of the area re the system is buried. It probably underlies much of the area he eastern half of the United States where the Carboniferous rocks stitute the uppermost formations, and considerable areas in the t where younger formations conceal it. Strata of equivalent age st underlie much of the sea.

The absence of the Devonian strata in certain situations is hardly significant than their presence at others. Thus it is to be notice that between Iowa and Indiana Devonian formations do not appea at the surface between the Siluria on the north and the Carboniferou on the south. The absence of Devonian beds here might indicat either that the deposits of the Carboniferous period extended farthe th than those of the Devonian, concealing the latter, or that Devo n beds, once deposited north of the present border of the Carbon ous system, were worn away before the deposition of the latter these alternatives, the former was, until recently, regarded th re probable; but a recent find near Chicago (at Elmhurst[1]) show t the Devonian system, or some part of it, once covered a por of the area where the Silurian beds now appear at the surface idence of the former extension of a formation over an area wher loes not now occur is usually found in the form of outliers (see Fig. 18 l p. 393); but in this case, the Devonian remnant does not constitut



201.—Figure illustrating the oc- rrence of remnants of Devonian aterial in fissures in Niagara lime- one, near Elmhurst (Cook Co)., linois.

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[1] Weller, Jour. Geol., Vol. VII, pp. 483–8.

an outlier in the usual sense of that term. The remnant, quantitatively insignificant, occurs in a fissure in the Niagara limestone, as illustrated by Fig. 201. The limestone was apparently fissured before the Devonian above was deposited. Portions of the Devonian sediments fell into an open fissure, carrying with them distinctive fossils (fish teeth). In this protected position, the Devonian fossils escaped removal.

About much of the pre-Devonian area of southern Missouri, the Carboniferous and Silurian beds stand in the same surface relations as in northern Illinois, though Devonian probably appears between these systems in the southwestern part of the State. It is thought by some that most of the Ozark area was land during the Devonian period, and that the Carboniferous sea lapped up on it farther than the Devonian sea had done. The alternative view has been mentioned (p. 433). Similar relations are repeated in the Black Hills, in Texas, and at other points in the west, where the Devonian system outcrops more rarely than any other system of the Paleozoic except the Silurian.

As in the case of other systems, it is to be remembered that the line on the surface marking the junction of the Devonian with older formations in any particular region is not the line which marks the limit of the Devonian sea in that region. Erosion has shifted the outcrop of the system, and therefore the line of its junction with older formations. Erosion, too, has reduced the aggregate area of the Devonian as originally deposited.

Igneous rocks.—The general absence of igneous rocks in most parts of the well-known Devonian of the continent is to be noted; but in many parts of the west, and also in central New York,[1] the Devonian strata have been affected by dikes and intrusions of later times, and in Nova Scotia and New Brunswick there are igneous rocks which appear to be of Devonian age.[2]

CLOSE OF THE DEVONIAN.

The general period of quiet which had prevailed during the Devonian seems not to have come to an end at its close. Only in the eastern part of the continent, in Maine, Nova Scotia, New Brunswick, and

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[1] Matson, Jour. of Geol., Vol. XIII., p. 264.

[2] Williams, Jour. of Geol., Vol. II, pp. 17-19.

e adjacent region to the north, do the Devonian strata appear to
ve been notably disturbed at the close of the period. Here the
vonian strata are overlain unconformably by the Carboniferous.
sewhere the formations of the younger system rest on those of the
ler without stratigraphical break.

ECONOMIC PRODUCTS.

Gas and oil.—The Upper Devonian is the chief source of oil and
s in western Pennsylvania[1] and southwestern New York, and is one
the sources in West Virginia,[2] the oil being derived chiefly from
rous beds. The Middle Devonian is the oil-producing series of
tario (Enniskillen).

Within the regions of their occurrence, oil and gas are more likely
be found under low anticlines than in other positions, for the apparent
ason that these furnish an inverted basin capable of holding these
ht substances against the superior pressure of subterranean waters
ich tend to force them to the surface. In all cases there must
parently be an impervious bed or combination of formations above,
prevent the escape of the oil and gas, and in this there is a certain
nilarity to the conditions requisite for artesian wells, but with the
fference that the artesian wells receive their supplies from above
d must be closed below, while the oil and gas wells receive thei
pplies from below and must be closed above. Both require a porou
d as a reservoir which, in the one case, ideally—but not alway
tually—forms a basin concave above, in the other, concave below
is the general opinion of geologists that the oil and gas of the Devonia
ds were derived from organic matter entrapped in the strata below
ough distinguished chemists suggest an inorganic origin for man
most such products.[3]

The lower part of the Chattanooga shale of central Tennessee i
e horizon of black phosphates, which are of considerable impor
nce commercially.[4]

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[1] For report on the oils and gas of Pennsylvania, see Carll, Rept. I, 5 Penn. Geol
rv., 1890. For statistics on the production of oil, gas, etc., see Mineral Resource
the United States, an annual publication of the U. S. Geol. Surv.

[2] White, West Virginia Geol. Surv., Vol. I, Oil and Gas, pp. 208 and 212. Thi
lume is an important contribution to the literature of oil and gas.

[3] Orton, 8th Ann. Rept., U. S. Geol. Surv., Pt. II, and White, op. cit. p. 180 *et se*

[4] Hayes and Ulrich, Columbia (Tenn.) folio, U. S. Geol. Surv.

THE FOREIGN DEVONIAN.

The continent of Europe.—At the close of the Silurian there seem to have been more considerable geographic changes in Europe than in America, for the Devonian system is there more commonly unconformable on its base. This is especially true in the northern part of the continent. When these geographic changes took place, a number of inclosed or nearly inclosed basins containing inland water-bodies appear to have been developed in northwestern Europe. This conclusion is based on the character of the deposits made in this part of the continent, and especially on the fossils which they contain. It will be seen that in a general way the phenomena on opposite sides of the Atlantic corresponded, for considerable areas in America likewise suffered warping, and similar inland basins of water or other lodgement areas came into existence.

During the progress of the Devonian period, the European continent was progressively submerged, as is shown by the fact that the Middle and Upper Devonian formations are more wide spread than the Lower (Fig. 202). In this respect, also, the phenomena of Europe are in partial correspondence with those of America, though the Middle and Upper Devonian of Europe overlap the Lower, and rest on older formations more commonly than in America.

In keeping with the geographic changes which the distribution of the Devonian formations of Europe indicates, the Lower Devonian strata of western Europe are for the most part such as to imply a progressive advance of the sea on the land, but not without oscillations. The greater abundance of limestone in the Middle Devonian shows that the waters were clearer than in the earlier stage of the period, while the wider distribution of the Middle Devonian, as compared with the Lower, points to less extensive areas of land whence sediments could be derived. As in America, the Upper Devonian of western Europe is more largely of clastic material than the Middle, though it also contains some limestone.

Though the Devonian formations are widely distributed on the continent of Europe, they do not appear at the surface over any large area, except east of the Baltic in Russia. A lesser but still considerable area of Devonian appears in the basins of the Rhine and Moselle rivers in western Germany, and in the adjacent parts of Belgium

and France. Aside from these larger areas, the Devonian is k in limited exposures at many points in the mountains of centra western Europe, in Germany, France, Austria, Hungary, Switzei Spain, Portugal, and Turkey. As a result of folding and faultin

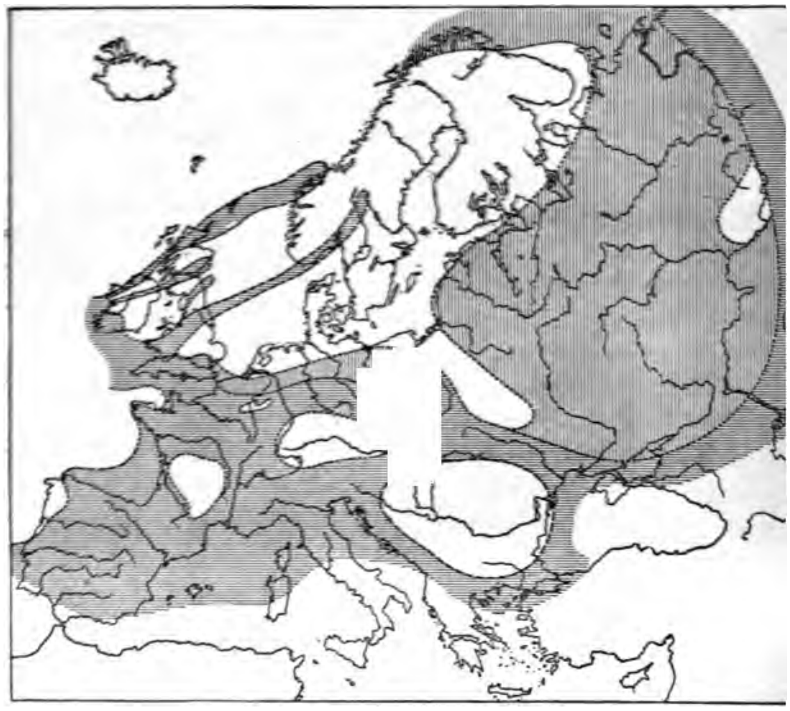

FIG. 202.—Sketch map of Europe during the Devonian. The horizontal lines sent the Lower Devonian; the vertical lines mark the additional areas the Middle Devonian occurs. (After de Lapparent.)

structure of the system is often very complex. Illustrations c complex structure are shown in Figs. 203, 204, and 205.

The Lower Devonian is often conformable on the Siluriar where the Lower Devonian is absent, and the Middle presen latter rests unconformably on the Silurian, or on any other forn which may happen to serve as its base. This is its relation t Cambrian in Belgium and northern France.

The areas where the Devonian beds outcrop are by no mea indication of their actual area, for they are to a large extent b *The Devonian* strata exposed in various parts of Russia are pro connected beneath younger beds. The Devonian system is also much more widespread in western Europe than its present outcrops indicate.

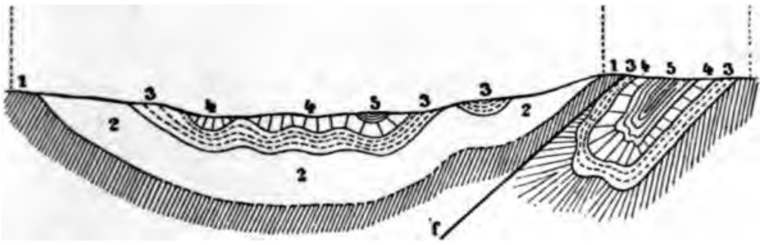

FIG. 203.—Section of the Devonian system of Dinant and Namur. 1 = Cambrian and Silurian; 2 = Lower Devonian; 3 = Upper Devonian; 4 = Carboniferous limestone; 5 = Coal Measures; *f*, fault. (Barrois.)

The British Isles.—In the British Isles the Devonian formation has two phases. The first is found in southwestern England in the area which gave the formation its name[1] (Devonshire). Here the system has a thickness of 10,000 or 12,000 feet, and, as shown by its fossils, is of marine origin. The structure of the Devonshire Devonian is so complicated that it is much less well calculated to furnish a key

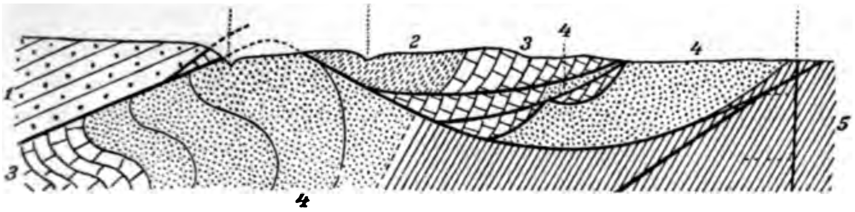

FIG. 204.—Section through the coal-field of Charleroi. 1 = Lower Devonian; 2 = Upper Devonian; 3 = Carboniferous limestone; 4 = barren, and 5 = coal-bearing Carboniferous formations. The heavy black lines indicate faults and overthrusts. (Briart.)

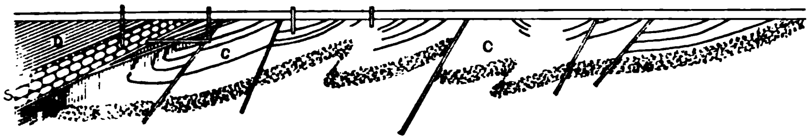

FIG. 205.—Section showing the coal-bearing formations, (*C*), beneath Devonian (*D*) and Silurian (*S*). *M* = Lower Carboniferous; *C* = Coal-bearing formations. (Pas-de-Calais; Barrois.)

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[1] The name Devonian was first used by Sedgwick and Murchison in 1839. Trans. Geol. Soc., 2d series, *Vol. V, p. 688.*

the history of Devonian deposition than the corresponding strat the Rhine basin. Igneous rocks are often associated with the sed ntary beds, and valuable ore-bearing veins sometimes result, as i von and Cornwall.

The second phase of the Devonian is the Old Red sandstone. Th at series overlies the Silurian and underlies the Carboniferou stratigraphical position is therefore clear, and it is thought to repr it the Devonian. This phase of the Devonian is widely distribut Wales, in west and north England, Scotland, in the Orkney ar etland Islands, and in Ireland. It is possible that certain beds rway, doubtfully referred to the Devonian, are to be correlat th the Old Red sandstone phase of the Devonian in the Briti es. The same phase of the formation likewise re-appears in weste issia.

Concerning the history of the Old Red sandstone there has been mu ference of opinion, but it is commonly held to have been deposited series of inclosed or nearly inclosed basins containing lakes or inla s, the waters of which were fresh or brackish. It is further belie at crustal warping gave the sea occasional access to these basi ese conclusions are based on the nature of the formation, and testimony of its fossils. In general the strata are poor in foss d those which are present indicate that the waters in which ata containing them were deposited were not the waters of en ocean. Some of the fossils are fresh-water species, while oth land species. At some horizons, however, marine species occ is not improbable that some portions of this singular series are baërial, rather than subaqueous origin.

Against this interpretation several objections have been urg the first place, the presence of occasional marine fossils is thou some to be against the inclosed-basin hypothesis.[1] The ans this objection has already been suggested. A second object found in the wide extent of the formation, if it be referred to a sin dy of water. As partially meeting this objection, it is said to obable that there was not a single inclosed sea or lake in wh ese beds were deposited, but rather many inclosed basins, and t one was necessarily very extensive. Neumayr [2] also finds a di culty in the way of the inclosed-basin hypothesis, in the great thickness of the Old Red sandstone, though admitting that it is no greater than that encountered in connection with other formations known to have been made in inclosed seas or lakes. The thickness of the beds is not very remarkable if they are interpretable as the results of inclined deposition.

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[1] Kayser and Lake, Text-book of Comparative Geology.

[2] Neumayr, Erdegeschichte, Vol. II, 1st ed.

The Old Red Sandstone formation, as its name implies, is mainly red and largely of sandstone. It, however, includes shales as well as sandstone, and the former, as well as the latter, are sometimes of a color other than that indicated by the name.

The Old Red sandstone of the British Isles is thought by Geikie[1] to have been deposited in several distinct basins. One of them extended westward from Scotland so as to include a part of Ireland, while another, that which includes the northern part of Scotland, the Orkney and Shetland Islands, perhaps extended eastward to southern Norway and finally still farther east to Russia.

It is to be noted that the Catskill formation of America has some features which suggest a comparison with the Old Red sandstone of Britain. Both are predominantly red, both are poor in fossils, and both seem to have been deposited in inclosed bodies of water. It is to be noted also that the one is in the eastern part of America and the other in the western part of Europe—regions where there are many other striking likenesses.

The Old Red sandstone formation of the British Isles consists of two great divisions, the upper of which in many regions lies unconformably on the lower. In such regions the lower division is conformable with the Silurian below, and the upper with the Carboniferous above. Since the Silurian below is not known to be the youngest Silurian, nor the Carboniferous above the oldest Carboniferous, it is not certain that the Old Red sandstone is the exact equivalent of the Devonian as elsewhere developed. It may include the upper part of the Silurian at its base, and the lower part of the Carboniferous at its top.

The lower division of the Old Red sandstone has a maximum thickness of something like 20,000 feet. It contains a large amount of volcanic rock. In this respect it corresponds with the Devonian

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[1] Trans. Roy. Soc. Edinburgh, Vol. XXVII, 1879. Also Text-book of Geology, 3d ed.

Germany. The aggregate thickness of the igneous rocks is, i cotland, as much as 6000 feet, and the rocks are, in places at leas gularly interbedded with the sedimentary series. The eruptio em to have been in part subaqueous, and in some cases so conside le as to build up the sea- or lake-bottom until it became land. e result of the great erosion which has since taken place, the igneo cks now form considerable ranges of hills (Pentland, Ochil, etc. here are thousands of feet of sedimentary rocks without volcan eds associated, both above and below the volcanic portions.

The upper division of the Old Red sandstone formation is not ick as the lower. The unconformity between it and the lower divisi a great one, and shows that changes of relations were taking pla a considerable scale. The bodies of water appear to have be ifted somewhat in position from time to time so that the formatio ade in one place at one time were exposed to prolonged erosion befo ey were again submerged and buried by younger strata.

In the upper division of the Old Red sandstone of Great Brita ere are conglomerates of such a character as to have raised a questi ncerning the existence of glaciers in this region in Devonian tim he conglomerates contain bowlders of all sizes, up to eight feet iameter. While the smaller stones are usually well worn, the larg nes are often distinctly subangular. All sorts of durable rock a presented. The large bowlders seem not to have come in from di nt regions, but some of the smaller stones may have come fro reater distances, since no local source for them is known. Furthe ore, some of the bowlders are said to be *striated*, and it is believ y some geologists at least that the striæ are glacial. The matrix e conglomerate is in keeping with the hypothesis that ice coöpe ted in its making. It has been suggested[1] that the Highlands cotland were then much higher than now, that they harbored glacie nd that the bergs to which the glaciers gave origin made, or help make, the conglomerates here referred to. The conglomerate be seen in the Lammermuir Hills, and in the Silurian hills of Cu erland and Westmoreland, in northern England.

Fossils of the " Old Red " type have been found within the Arct ircle on Bear Island (lat. 70° 30′ N.), between the coasts of Norw and Spitzbergen, and both divisions of the Old Red have been recognized in Spitzbergen.[1]

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[1] Neumayr, Erdegeschichte, Vol. II, p. 133.

West central Europe.—The Devonian of Germany is remarkable for the proportion of igneous rock interbedded with the sedimentaries. The igneous rock is principally diabase and diabase tuff, but other varieties are also found. These rocks occur in many separate beds, showing that there were many periods of igneous activity separated by intervals of quiet. Igneous rocks occur in the Devonian in some other parts of western Europe.

In much of central-western Europe the Devonian strata have been metamorphosed, and their structure is often complex. In not a few places, especially where the sedimentary rocks have been invaded by igneous rocks, mineral veins have been developed whence large quantities of iron, tin, copper, and other metals have been obtained.[2] The Devonian of Germany also contains a little coal, showing that the conditions for its formation were locally present.

Russia.—The Devonian of Russia is made up of beds of arenaceous and calcareous rocks, the former containing fossils related to those of the Old Red sandstone, the latter containing fossils of a marine fauna. The Lower Devonian appears to be wanting in much of Russia, and the middle and upper parts of the system are generally unconformable on subjacent formations. Except in the Ural region, where Lower Devonian is present, the Devonian strata of Russia are not notably disturbed.

Comparison with America.—On the whole, the course of geological history seems to have been less pacific in Europe than in America. The great local unconformities within the Devonian system find no parallel, so far as now known, in America, and the extreme development of igneous rock in western Europe is not duplicated in America.

In Europe as in America, there do not seem to have been notable changes at the close of the Devonian. There seem to have been some changes of level in Russia, Bohemia, and Great Britain, so that succeeding strata rest with some measure of unconformity on the Devonian; but over much of the continent the Carboniferous strata succeed the Devonian conformably. In this again the European phenomena correspond with those of America.

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[1] Geikie, Text-book of Geology, 4th ed., Vol. II., pp. 1012 and 1013.

[2] Ibid., p. 995.

)ther continents.—The Devonian system has a wide distribut ;iberia and China, where its faunal relations are with north ope. It is known in Asia Minor, Persia, and northwestern In nalayas and eastern Tibet). It perhaps has wide distribut North Africa (Atlas mountains, Sahara), in South Africa (C ›ny), and in the Falkland islands. Glacial beds of Devonian ; e been reported recently from South Africa.[1] The fauna of the Sou can Devonian has South American affinities. The system has c rable development in South America, and carries an indigen ıa akin to the Hamilton fauna of North America. So far as identif his continent, the Devonian beds are referable to the upper part Lower Devonian, and to the lower part of the Middle.[2] The syst ins a thickness of 10,000 feet in New South Wales,[3] Australia, a been recognized in Victoria. With the Middle Devonian se tary formations of Victoria, felsitic lavas and tuffs are associat onian(?) rocks are the oldest known formations of the North Isla · Zealand, and attain great thickness—7000 to 10,000 feet[3]—in th Island. Kayser[4] recognizes two great Devonian provinces, v *Eurasian*, including a large part of north and central Asia, and pr ' extending to Manitoba, and the *American*, including much of ted States, South America, and South Africa.

DEVONIAN LIFE.

I. THE MARINE FAUNAS.

;eneral faunal evolutions.—It may be recalled that the ea ine faunas of the Cambrian period were interpreted as regio ›rovincial in type, but were found to merge into a more gene : toward the close of the period. The Ordovician fauna was regar eally little more than a continuation and expansion of the Ca n fauna and as singularly general at its climax. After a repr ıl interval, the Silurian fauna seems to have developed into lar cosmopolitan type, followed by a restrictive evolution. It to be noted that the Devonian period, in America at least, broug

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;chwarz, Jour. Geol., Vol. XIV, p. 683, 1906.

Kayser, Geologische Formationskunde. [3] Geikie, op. cit., p. 999.

dem, Zweite Auflage, p. 154. Other and minor faunal provinces are defined ıden, Mem. du Comité geologica, XVII, No. 2, pp. i–x, and Barrois.

again an evolution of provincial faunas, but on an unusually large and declared scale, and of an advancing phase, verging toward cosmopolitanism.

The ancestors of the Devonian faunas are found remotely in the cosmopolitan fauna of the Silurian period, and more immediately in the restrictional faunas of the closing Silurian. The early Devonian faunas are to be regarded as the expansional phases of these restrictional faunas. Fortunately the physical conditions during the Devonian evolution are better known than those of previous stages when provincial faunas were undergoing development, and hence reveal in a specially instructive way the conditions under which such faunas develop. Even here, however, the data recorded are far from complete, and only a part of them have been critically studied as yet, so that whatever conclusions are now entertained must be held subject to correction. By way of precaution, it is to be recalled that the faunas here under discussion are those of the relatively shallow water that lay about the continental border, or on the bosom of the continent itself, in the form of intruding gulfs and interior seas. The land life, to be considered later, had its own independent phases of development, while the faunas of the abysmal depths of the ocean and of the surface of the mid-ocean are almost wholly unknown.

Special faunas evolved.—With the partial withdrawal of the sea from the North American continent, as sketched in the previous chapter, the mid-Silurian fauna underwent restrictive evolution and differentiation in the embayments on the continental border. For want of free communication between these embayments, their faunas developed distinctive aspects. When the sea re-advanced upon the land in the early Devonian, it was by tongues or invading gulfs from different points on the continental border, these being in part extensions of the border embayments. Each of these gulfs seems to have had its own rather distinctive fauna, inherited from the embayments of the coast border.

Five such faunas seem to have invaded the continent of North America during the Early and Middle Devonian, partly in succession and partly simultaneously, viz.: (1) the Helderberg, (2) the Oriskany, (3) the Onondaga (Corniferous), (4) the southern Hamilton, and (5) the northwestern Hamilton. These reached the interior in succession in the order named, and the faunas are described mainly as y are found to have been developed at the stage when they suc ded one another in the interior, but all must have had earlier stage ·ing which they were evolving and advancing upon the continen ng their particular lines of invasion. As each in succession cam ɔ contact, through the coalescence of the advancing gulfs or sea h the fauna that had previously invaded the region, there was ımingling and conflict of the various assemblages, resulting in th nination of some species and the adjustment of others to one anothe ɘ result was a fusion of the forms surviving from the two fauna l the development of a new composite fauna. In this fusion, on the other of the faunas was usually dominant and gave the chi ıracteristics to the new fauna.

The originating tracts of the invading faunas.—The places of origi these faunas cannot be determined at present with certainty, bu following are the suggestions of present evidence, and may serv working hypotheses until fuller data shall establish permane ɘrpretations. Of the Helderberg fauna, the more local elemen bably originated in the great embayment at the mouth of the S wrence and on the border of the adjacent continental shelf. T local element seems to have been derived from the coast bord he (then) North Atlantic, which seems to have connected the Ame continent with southern Europe, but not directly with northe rope. The Hercynian fauna which characterizes this stage of t vonian in southern Europe has much in common with the Held g fauna of America, while both were markedly different fr early Devonian fauna of northern Europe and northern Ameri hough a fauna of Helderbergian aspect has been detected at c ality in the far northern islands.[1]

Giving precedence here to the local American phase, it is to ed that in the St. Lawrence embayment the strata show a grad ssage from the Silurian fauna up into the Helderberg fauna. l be recalled that the St. Lawrence embayment was a harbor uge for the Ordovician life when it was forced to retire and unde nsition into the Silurian type. History seems to have acqui habit of repeating itself thus early. The Helderberg fauna see have advanced from the coast-border region of the Middle Sta o the Appalachian valley trough, and to have spread westwa and northward as far as the advancing waters permitted. If the interior waters did not extend southwesterly to the Helderberg areas of Tennessee, Illinois, and the Indian Territory, the access to these regions was probably gained through embayments from the more southerly coast. The fauna seems never to have occupied the great interior Mississippian region generally.

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[1] Meek, Am. Jour. Sci., ser. 2, Vol. XL, p. 31.

The Oriskany fauna, which followed the Helderbergian in this region, appears to have entered the interior region along the same tracts as the Helderbergian, but to have spread farther westward, even as far as western Ontario, while the Helderbergian fauna only reached central New York. In its dominant phase, it was a sand-loving fauna and crept along the arenaceous tract adjoining the old Appalachian land and the northern shore of the interior sea. In other areas where the deposit was calcareous, the fauna assumed a modified phase.[1] The general identity of its lines of invasion with those followed by the Helderbergian fauna, and the occurrence of species of Oriskany aspect in the St. Lawrence embayment, offer some suggestion as to its place of origin. A very significant fact also is the occurrence of some very peculiar Oriskany-like species in South America. This hints at the possibility that the fauna either developed along the Atlantic coast in a horizon now entirely buried, and certain of the species spread down the coast and reached South America, or else, originating at the south, certain species spread up the coast until they found access to the interior through the inlets mentioned. Some part of the fauna perhaps spread on to Europe and to Africa, or else was derived thence and spread westward, since allied species occur in those regions. It is also quite possible that some notable part of the fauna developed in the St. Lawrence embayment at a stage later than the evolution of the Helderberg fauna, when the deposits became sandy, as they did, and that thence there was migration more or less simultaneously southward along the coast to South America, westward into the interior, and northward and eastward to Europe and Africa. The more typical species of the Oriskany, however, do not seem to have been directly derived from Helderberg species, but to have been evolved in some distinct area. The typical Oriskany fauna, on invading the regions already occupied

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[1] Clarke, J. M., Mem. N. Y. State Mus., No. 3, Vol. 3.

the Helderberg fauna, mingled with it and hence a Helderber
ıent was present.

As to the originating tract of the Onondaga fauna, still less is know
in its maximum extension it occupied the whole of the great interio
sissippian sea, which had not been the case with either of the pr
ng faunas. A very characteristic development of this fauna
ıd along the north side of the interior basin in the vicinity of th
its of Mackinac, and the suggestion hence arises that the faun
ıded the interior sea in this region from the north, along a tra
n which the deposits have since been removed (see map, Fig. 193
s than three hundred miles to the north, in the James Bay basi
fauna has much the same facies as that nearest it on the sout
ile there is no positive evidence of a former connection across t
rvening tract, there seems to be no inherent improbability in su
nection.[1] Besides these geographic relations there are gener
siderations, as will be seen later, for believing that this fau
a northern origin, and had communication with northe
ope.

Almost the only light on the originating tract of the eastern Ham
fauna is found in the fact that a very similar fauna lived in Sou
erica (Bolivia, Brazil, and the Falkland Islands) at about t
ıe time, and that some quite peculiar forms are common to t
.[2] A southern origin seems therefore the most probable, and t
ı reasonable harmony with the distribution of the strata conta
it. It is hence inferred that this fauna entered from the sou
ıg the Mississippi tract, which may not improbably have be
n at this time, as there is direct evidence of land subsidence in t
ction.

Concerning the northwestern Hamilton fauna,[3] there is evide
t it gradually crept down from the north, probably along the tr
t is now the Mackenzie valley, and that for a time it was not
ımunication with the area occupied by the southern Hamilt
that at length it passed over the intervening barrier that seems
e stretched from the old lands of Wisconsin to the similar old la
Missouri. Thence it invaded the eastern interior sea and over

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[1] Weller, Jour. of Geol., Vol. X, p. 423.

[2] Williams, Bull. U. S. Geol. Surv., No. 210, p. 79.

[3] Williams, idem.

the territory already occupied by the southern Hamilton fauna[1] (see map, Fig. 196).

Bearing in mind that these suggestions relative to the origin and invasion of the America interior by these great provincial faunas are subject to correction by new data, they may be taken provisionally to represent the leading faunal movements of the early and middle Devonian in the interior and eastern portions of the continent. These successive invasions may be likened to the barbarian invasions of southern Europe in medieval times. As in the latter case, the precise origin of the invading hosts is subject to doubt and can only be approximately inferred, but the later stages of the invasions and their consequences are more or less clearly discernible, and constitute the most declared features of this romantic period.

In the Great Basin there seems to have been a very slow and conservative evolution as though the area was largely isolated, or at least protected from such faunal inundations as those that overwhelmed the eastern region. This region and that of the Pacific coast will be treated later.

The Helderberg Fauna.

Assuming that the Helderbergian fauna was derived from the Silurian fauna, it should have been differentiated from it in a less degree than were the Oriskany, Onondaga, and Hamilton faunas at the time of their respective invasions, for less time had passed previous to its appearance in the interior. This is conspicuously true. The fauna bears a strong Silurian facies, and, on account of this, has often been classed as Silurian. It had, however, undergone so much change from the parent fauna that, with but two exceptions, so far as now known, the species were all new. These two exceptions were the cosmopolitan species *Leptæna rhomboidalis* and *Atrypa reticularis*, species remarkable for their wide range and long life. Considered as species, they were the Methuselahs of the Paleozoic times.

In that portion of the originating tract that lies in the St. Lawrence embayment, there are over 2000 feet of shales and shaly limestones, forming a continuous series, in the lower part of which the fossils are predominantly Silurian and in the upper part predominantly Devonian, while in the central thousand feet the two types are commingled or

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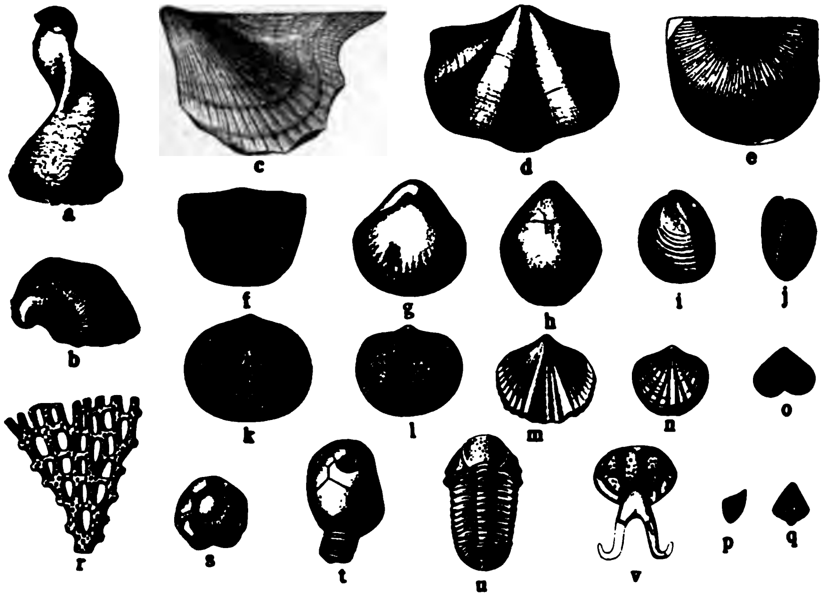
[1] Weller, Journ. of Geol., Vol. VI, p. 306.

replaced by intermediate forms. From this intermediate or tran
ıal assemblage the Helderberg fauna seems to have taken its orig
ɔart at least, and to have emigrated westward as the re-advan
he sea permitted.

The marked development of the mollusks.—As the physical co
ons in the originating tract gave a muddy, partially calcareo
:om, the fauna developed in lines suited to such a habitat an
ike conditions prevailed in the interior to which it emigrated,
ined its original character as a silt-conditioned fauna. As a co
ıence, mollusks and molluscoids greatly preponderated, and tril
s were fairly developed, while corals and crinoids, lovers of cle
er, were relatively few and unimportant. The gastropods can
unusual and quite peculiar prominence. The capulids, a rath
rior or degenerate type, seem to have found singularly congeni
litions, for they appeared in great variety of form. Two characte
forms of this group are illustrated in Fig. 206, *a* and *b*. T
ıp continued to play an important part in the faunas that occ
the interior in succession during the following stages of the Dev
period, whether because, having come in with the Helderbe
ıigrants, they held their own notwithstanding the subseque
ısions by other faunas, or because new forms came in with ea
hese invading faunas, does not now clearly appear, though t
ıer seems the more probable. Especial interest attaches to tl
ıp because it constitutes one of the characteristic features of t
cynian fauna in Europe, a fauna which has been the subject
h difference of opinion but which is, with little doubt, the essent
ivalent of the American Helderberg. A number of gastropc
r than the capulids were present.

The bivalves also blossomed out notably in large-winged forn
aviculids (Fig. 206, *c*). This was in sharp contrast to the Niaga
ıa, which showed but few of these forms. Like the capulids, th
inued to be numerous through the succeeding Devonian fauna
Quite in contrast with the foregoing, the cephalopods had a ve
ger development. From being one of the dominant types in t
rian, they fell to an insignificant rank. They were to rise agai
ever, in a new form.

The superior numbers of the molluscoids.—The inevitable brachi
s far surpassed all other classes in numbers. They were even mo



IG. 206.—The Helderbergian Fauna. *Gastropoda: a, Platyceras spirale* Hall; *b, Platyceras gibbosum* Hall, two forms of the capulid shells which abound at some localities in the Helderbergian and which have their great development in the Devonian faunas. *Pelecypoda: c, Actinopteria textiles* (Hall), one of the winged pelecypod shells which have so great an expansion in the Devonian faunas. *Brachiopoda: d, Spirifer macropleurus* (Con.), a species which is more closely related to the Silurian than to the Devonian members of the genus; *e, Strophonella punctulifera* (Con.). The members of this genus are more characteristically Silurian than Devonian although it persists to the Middle Devonian; *f, Leptæna rhomboidalis* Wilck., a species which ranges from the Ordovician to the Mississippian (see Fig. 163); *g, Gypidula galeata* (Dal.), one of the most characteristic species of the Lower Helderbergian or Coeymans fauna; *h, Rensselæria æquiradiata* (Con.), a representative of a genus peculiarly characteristic of the Lower Devonian; *i, Uncinulus mutabilis* (Hall), a representative of a genus of rhynchonelloid shells which has its greatest development in the Helderbergian faunas; *j, Schizophoria multistriata* (Hall), and *k, Rhipidomella oblata* (Hall), shells representing two types of orthids having their greatest development in the Devonian faunas; *l, Dalmanella subcarinata* (Hall), another orthid of a group more strongly represented in earlier faunas; *m, Eatonia medialis* (Van.), a representative of a genus most characteristic of the Lower Devonian faunas; *n, Atrypina imbricata* (Hall), a lingering Silurian type; *o, Bilobites varicus* (Con.), a type of orthid characteristic of the Silurian and Helderbergian; *p–q, Cyrtina dalmani* Hall, a member of a genus feebly represented in the Silurian but which has a great development in the Devonian faunas. *Bryozoa: r, Polypora lilæa* (Hall), one of the fenestelloid bryozoans, a group having a slight representation in earlier faunas, but attaining great prominence later. *Corals: s, Michelinia lenticularis* Hall, the earliest member of a genus of corals which becomes abundant in later Devonian faunas. *Cystoidea: t, Lepocrinites gebhardii* Con., one of the last representatives of the cystids, a group of echinoderms having their greatest expansion in Ordovician and Silurian times. *Trilobita: u, Phacops logani* Hall, the genus Phacops, though present in the Silurian, has its great development in the Devonian; *v, Dicranurus hamatus* (Con.), an acidaspid whose closest relative occurs in Barrande's étage *G*, in Bohemia. (Weller.)

nerous in genera and species than in the Silurian period, but di develop such tangible peculiarities as the gastropods and pelec ls. Illustrations of leading forms will be found in Fig. 206, *d* to ere were many members of the *Orthis* family (Fig. 206, *j*, *k*, and ich gave a somewhat Silurian facies to the fauna, but a study details of these forms shows the initiation of the Devonian ty levelopment. The members of the *Strophomena* family (Fig. 206, *e*, e also very abundant and much diversified, a foreshadowing ir much greater development in the succeeding Onondaga ar milton epochs. The spirifers (Fig. 206, *d*) had come to be a striki ture of the assemblage. They had made a very notable advan on their relative place in the Silurian fauna. Several of the Held g spirifers were clearly successors of Silurian species and represe secutive evolution, but a larger number were not so much lingeri resentatives of known earlier forms as initial forms of new ty ich were to be more fully developed in the succeeding Devoni nas. The loop-bearing brachiopods appear at this time in t us *Rensselæria* (Fig. 206, *h*) which reached its maximum devel nt in the next epoch.

The bryozoans were fairly developed and foreshadowed comi es, rather than represented past types (Fig. 206, *r*).

The aberrant tendency of the trilobites. — The trilobites guished the epoch by their notable tendency to sport, a tender ich reached its climax later. They took on strange and distinct ns, one of which is illustrated in Fig. 206, *v*. The peculiar sha the head parts and their remarkable ornamentation seem inex le unless they had an esthetic function, which would presupp high mental development. But, whether explicable or not, elopment of the ornamented and erratic forms represents a st the evolution of the class quite worthy of note, not only as charact c of the Devonian evolution, but as a precursor of the approach appearance of the whole group. It will be seen later that as obites neared the end of their career their forms became aberra

The scantiness of the crinoids and corals.—The crinoids had fal m their former high estate in the Silurian to an insignificant pla fatally and finally, but temporarily, on account, we may s e, of the rather turbid waters which the shales and shaly consti s of the limestones indicate. The cystids (Fig. 206, *t*) suffered l relatively, but they were not abundant. The other echinoderms were still less important.

The corals, doubtless for like reasons, were not generally abundant, though *Favosites* was well represented, as were also a few other forms. The genus *Michelinia* (Fig. 206, *s*), which became abundant in the Onondaga and Hamilton epochs, makes its first appearance here.

Minor forms.—There were hydrozoans, among which *Stromatopora* became so common as to form, almost alone, beds three or four feet thick; a few graptolites, which were about to become extinct; some sponges, and doubtless not a few other forms that have escaped fossilization.

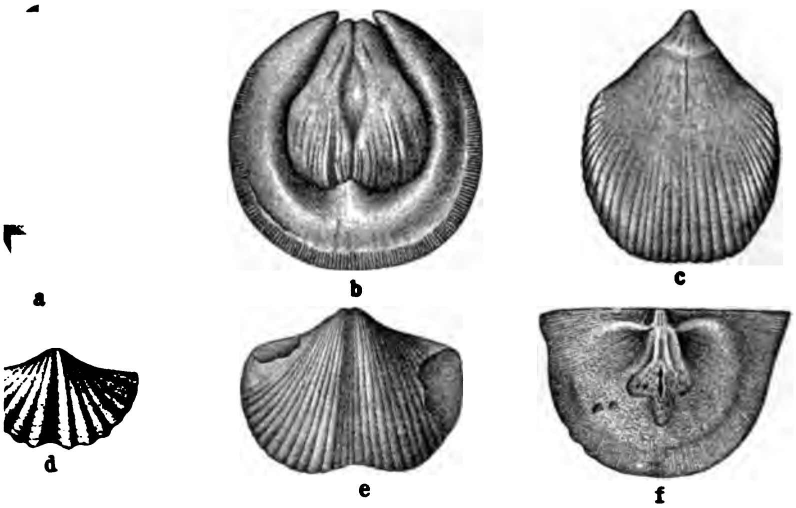
The notable absence of fishes.—It is to be especially noted that fish remains are almost or quite absent from the Helderberg deposits, although they had appeared in the epoch just preceding and reappeared in great abundance and in remarkable forms in the Onondagan epoch that soon followed. However their absence is to be explained—and it seems to be nearly inexplicable—it serves to strengthen the belief that the Onondaga fauna originated in a tract well isolated from the originating tract of the Helderberg fauna.

The Oriskany Fauna.

The key to the interpretation of the typical Oriskany fauna appears to lie in the fact that it was a sand-loving assemblage of species and that its habitat was the sand-flats that skirted the ancient shore belt. There was a minor phase of the fauna found in calcareous deposits. The fauna was bound by many close ties to the Helderberg, especially that phase of it which is present in the more calcareous beds, but it contained also distinct features implying in part a separate origin. However originated, it was so constituted as to fit the conditions of shallow water and sandy bottoms, while the Helderberg fauna was adapted to calcareous and muddy bottoms, and perhaps to somewhat greater depths. The Oriskany fauna, as we know it, was also later than the Helderberg, which means that in so far as it was not derived from the Helderberg, it had been developing longer since the two diverged from a common stock, and should therefore be farther removed from the common Silurian parentage. Whatever the source of the Oriskany fauna, it appears to have been developed outside the interi

and to have followed the Helderberg fauna into the interior as
tinct invasion.

reponderance of large brachiopods.—More than half of all the known
es of the Oriskany fauna are brachiopods.[1] Their most obvious
re was their great size. The *Pentamerus oblongus* (Fig. 187, *o*)
e Silurian period and a few other previous forms had been large,
it no time had there been a fauna made up of species from differ-
genera and even different families which attained such ample



207.—The Oriskany Fauna. *Brachiopoda: a, Rensselaria ovoides* (Eaton);
presentative of a genus restricted to the Helderbergian and Oriskany (see Fi
6, (*h*); *b*, *Hipparionyx proximus* Van., one of the most characteristic fossils
e arenaceous Oriskany beds; *c*, *Camarotœchia barrandei* (Hall), one of the larg
ynchonelloid shells of the Oriskany; *d*, *Spirifer murchisoni* Castel, and *e*, *Spirif*
enosus (Con.), two of the most characteristic Oriskany species, the first occurrin
roughout the fauna, the second mainly in the fauna of the arenaceous beds;
ropheodonta magnifica Hall; a species which sometimes grew to be four or fi
hes across. The genus has its great expansion in the Devonian. (Weller.)

nsions as those of the Oriskany. *Spirifer arenosus* (Fig. 207, *e*
selæria ovoides (Fig. 207, *a*), *Stropheodonta magnifica* (Fig. 207, *f*
parionyx proximus (Fig. 207, *b*), and *Camarotœchia barrandi* (Fig
c), all reaching lengths or breadths of two and one-half to fou
s, made up an aldermanic group that seems all the more notabl
ts sandy habitat, though sandiness at the bottom of the sea doe
mply sterility in the same sense as sandiness on the land. Ther
small brachiopods associated with these giants, but they we

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[1] Schuchert, Rept. N. Y. State Geologist for 1888, p. 51.

less impressive as a factor of the fauna. The brachiopods of the Oriskany were largely of the same genera as those of the Helderberg, but the species were new. Some of the genera, as *Eatonia* and *Rensselæria*, were confined to these two faunas; others had a wider range. Of the latter, many were represented later in the Onondaga, and some in the Hamilton faunas.

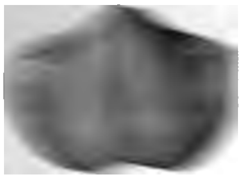
It is important to note that in South America there were several species which bore a strong Oriskany facies, and in some cases there was complete specific identity, as in the notable form *Anoplotheca flabellites*.

Mollusks abundant and large.—While the mollusks were much less amply represented than the molluscoids, they showed some striking characters which help to further characterize the fauna. The gastropods were the most abundant of the mollusks, and the capulids were their leading form, as in the Helderberg epoch. Not less than 60% of all the known Oriskany gastropods were capulids. Some of them were exceptionally large and plump, reaching lengths of four inches, and mouth-expansions of two and a half inches. The Helderberg capulids had been without spines, but the spine-bearing species *Platyceras nodosus* appeared in the Oriskany fauna, although it became more conspicuous in the later Onondagan.

The pelecypods were not very abundant, but, like the brachiopods and gastropods, they were phenomenally large and coarse, some of them being five inches across. These unusual sizes, affecting three distinct types, imply that the cause lay in conditions congenial to the types and not in the types themselves, except as they were well constituted to respond to the conditions. The pteropods were represented by the *Conularia*—and even that was large—and by large tentaculites; while the former powerful cephalopods were reduced to a single species, so far as the known record shows.

Scantiness of trilobites, corals, crinoids, and fish.—The trilobites were not abundant and were chiefly species that had a larger development in the Onondaga. They were perhaps even Onondagan forms that became mingled with the late Oriskany forms after the two faunas came in contact, as explained later. In the calcareous phase of the Oriskany, however, there were several trilobites more or less closely allied to Helderberg forms. Corals, crinoids, and cystoids were rare, as might be expected from the nature of the formation; so also were

[illegible]



[illegible]

bryozoans and most of the minor types. Fishes were also wanting, ugh the reason is not evident. In a word, the Oriskany fauna was ntially an assemblage of well-fed mollusks and molluscoids with ant sprinkling of other forms.

There was a fauna in South America that contained Oriskany-like ns. The Helderberg type is not known to have preceded it there. wide-ranging habitat along the coast of the Atlantic, which this ns to imply, was probably the main home of the fauna, and its rsion into the interior was probably but an episode in its history ch happens to have been better recorded than the main chapter.

The Onondaga Fauna.

The presence of true marine fish.—The Onondaga fauna is most kingly distinguished from the preceding ones by the appearanc host of fishes of highly developed and divergent types. There i reasonable ground to doubt that these were true marine fishes atever may have been true of the fishes of the late Silurian an the transition beds discussed in the last chapter, and of the Ol l Sandstone fishes to be discussed later in this chapter under th d of fresh-water life. The Onondaga fishes were intimately asso ed with marine invertebrates of the most typical kind, and in th st typical way, and there were none of those peculiar association h gigantic crustaceans, land plants, and a strange pauperitic grou invertebrates, which seemed to place the previous fish faunas in cial category. Confirmatory of the true marine character of thes es is the fact that they had successors in the succeeding marin osits, and left a consistent record from that time to the present tead of occasional and sporadic appearances in special localities h as characterize the record from the Ordovician period up to thi e (and which perhaps merely imply occasional incursions or inwashe m land-waters), there was now a continuous occupancy of the seas from this time on fishes ranged widely through the epicontinenta ters of America and of Europe, and doubtless of the seas generally eir numbers in the Onondaga waters were very great, though th of known genera and species is small. A notable feature of th ord consists of "bone beds," thin layers made up almost exclu- ely of the plates, teeth, spines, and dermal ossicles of fishes whose mbers must have mounted into the millions. One of these occurs r Columbus, Ohio, and another near North Vernon, Indiana. Newberry[1] describes the relics as fragmentary and worn, and suggests that they may be the undigested residue of innumerable feasts of the larger fishes upon their weaker kin. It is possible that there were restricted tracts or passageways of the shallow sea through which the inferior fish habitually passed for reasons connected with the depths, currents, tides, food-distribution, or other sea conditions, and that in so doing they were the victims of persistent attacks by their superiors, and thus the bottom became strewn with the débris of the slaughter. At the present time, sudden changes of temperature due to the shifting of currents destroy great numbers of fish simultaneously and probably give rise to great fish deposits. Were it not for the fragmentary condition of the relics of the ancient bone beds this would seem to offer the most plausible explanation.

The fragmentary nature of the remains makes a satisfactory identification and classification difficult and not a little revision of those first made has been found necessary; still further changes will doubtless yet be required. What is said about kinds and classes must therefore be taken with some reserve. It is clear, however, that an extinct order of fishes, arthrodirans (joint-necked), formed a signal feature of the fauna; that sharks of several orders also constituted a large element; that certain of the ancient ganoids (crossopterygians), were present, and doubtless other forms. The arthrodirans, whose necks were so joined to their bodies as to give their heads vertical motion, a rare feature in fishes, were quite remarkable forms, and perhaps held the leading place. Among them were the *Macropetalichthys*, whose skull is illustrated in Fig. 208, *a*, and *Dinichthys* (terrible fish) which rose to monster sizes a little later (Fig. 209, p. 463) and then rapidly declined. The sharks embraced not only forms armed with cutting and piercing teeth, but also forms provided with pavement teeth for crushing shell-fish. The *Teleostomi* were of the ancient type (ganoids, chiefly crossopterygians) which were usually characterized by cartilaginous skeletons and bony scales, in contrast to modern teleosts, which are characterized by bony skeletons and membranous scales. In general the fishes of the time seemed to have been more fully clothed with spines and defensive armor than modern fishes. Compared with existing species they were doubtless heavy and clumsy in movement, and sluggish and brutal in habit.

From the degree of adaptation to sea conditions already attained,

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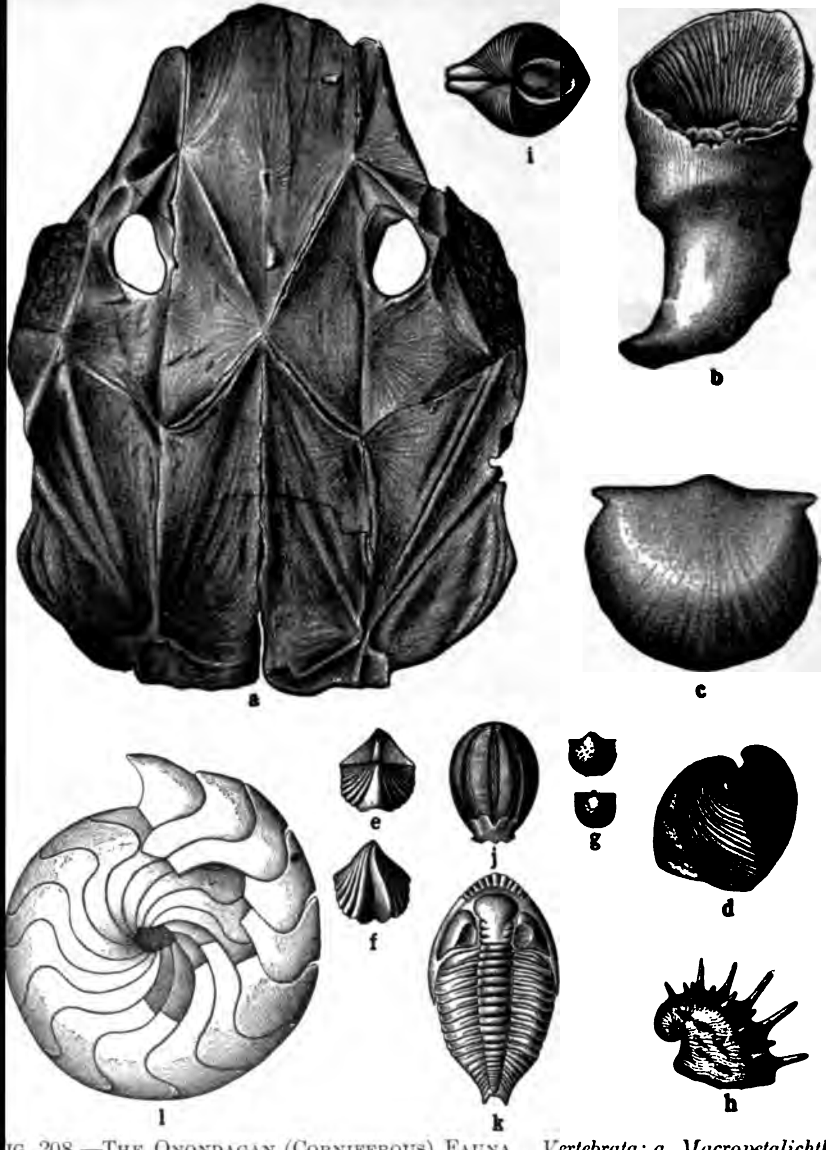
[1] Paleozoic fishes of North America, Mono. XVI, U. S. Geol. Surv., 1889, p. 30.



IG. 208.—THE ONONDAGAN (CORNIFEROUS) FAUNA. *Vertebrata: a, Macropetalichth sullivanti* Newb. The figure represents the head of one of the most characteris Onondaga fishes. *Coral: b, Zaphrentis ponderosa* Hall. The figure represents medium-sized, simple, horn-coral. *Brachiopoda: c, Stropheodonta concava* Hall, a *d, Spirifer acuminatus* (Con.), two of the most characteristic Onondaga brachiopo *e, f, Cyrtina hamiltonensis* Hall, two views of a species having a wide geograp distribution, and a long geologic range in the Middle and Upper Devonian faun *g, Productella spinulicosta* Hall, one of the earliest representatives of a genus whi became wonderfully abundant in the Upper Devonian, and gave rise to the typi *Productus* of the Mississippian and Carboniferous faunas. *Gastropoda: h, Platyce*

[*Continued on bottom of p. 463.*]

it is probable that they had been living for some time in the sea in the originating tract of the Onondaga fauna somewhere in the northern region. It is not impossible that fish were inhabitants of the northern seas from the late Silurian on, but not of the more southerly seas previous to the time of this invasion, since their relics are absent from the preceding Helderberg and Oriskany formations. Several of the genera of the arthrodirans and sharks have been found in the deposits of Germany (*Dinichthys*, *Macropetalichthys*, *Machæracanthus*), implying that they lived in the interior sea of Europe as well as that of America.

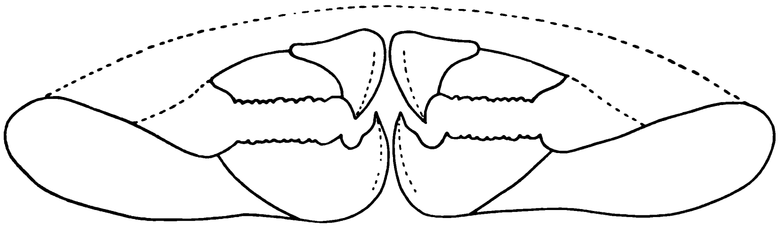


FIG. 209.—Diagrammatic front view of the dentition of *Dinichthys herzeri*, Huron shales, Delaware, O. (After Newberry.)

Others (*Acanthaspis* and *Onychodus*) have been recognized in the Lower Devonian deposits of Spitzbergen, directly supporting the suggestion of a northerly distribution.

The profusion of corals.—Another significant feature of the Onondaga fauna was the extreme abundance of corals. From the rapids of the Ohio at Louisville there have been collected more than two hundred species deemed worthy of illustration. Other localities add greatly to the total list. These embrace both the simple cup form (Fig. 208, *b*) and the compound type. Some of the former reached extraordinary sizes, as in the case of *Zaphrentis gigantea*, individuals of which sometimes attained a length of eighteen inches and a diameter of three inches. The general range in size was wide, small and large being intermingled, though the large preponderated. The salient expression of the epoch, however, lay not so much in the advance of

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dumosum Con., a capulid shell with large, hollow spines. *Pelecypoda: i*, *Conocardium trigonale* Hall, a dorsal view of a common Onondaga pelecypod. The genus occurs in the Silurian and also in the Mississippian. *Echinodermata: j*, *Nucleocrinus verneuili* (Troost), a blastoid which occurs in great numbers in one layer of the Onondaga limestone in the Ohio valley. *Trilobita: k*, *Odontocephalus ægeria* (Hall), one of the dalmanites, showing the development of ornamentation on the border of the head and tail. *Cephalopoda: l*, *Tornoceras mithrax* (Hall). This is the first goniatite to appear in the faunas of America. The goniatites are distinguished from earlier representatives of the cephalopods by their lobed sutures. (Weller.)

:orals as organisms as in their great luxuriance and relative prom
e. The reef-building habit which had appeared in the Niagar
h reached a fuller expression at this time, the reef at the rapic
ıe Ohio being the most famous example. This luxuriance of th
s implies clear seas abundantly enriched with floating organi
er. This seems in turn to imply that the higher lands and steepe
es which had perhaps given a notable inwash of sand and silt du
:he two previous epochs had given place to lower land, doubtle
ely clothed with vegetation—the result, very likely, of an approac
ase-leveling.

'he unequal development of the crinoids.—That the profusion c
ls, however, did not find its sole explanation in clear genial wate
in food may be inferred from the relative poverty of the same se
rinoids which affect like conditions. In the Niagara epoch th
oids and the corals flourished together in luxuriance. In th
ndaga, the corals were phenomenally prolific, while the crinoic
:, with local exceptions, rather scant. This is the more remarl
in view of the subsequent, as well as previous, abundance of th
oids. That the physical conditions were not uncongenial seen
e shown by the fact that the individuals present were usually lar
bore no signs of repressive environment, but rather the opposit
repressive conditions are possibly to be found in some untowa
ıre of the transition from the Niagara epoch, which gave prec
:e to their competitors, the corals, an advantage which they he
ughout the epoch to the measurable exclusion of the crinoic
lse in some undeterminable organic agency.

'ystoids have not been found. They were far down their declini
e to be sure, but were not yet extinct, for they appear in the f
ng period. The blastoids were represented (Fig. 208, *j*), but t
r echinoderms, like the cystoids, have not been found, and the
r branches were yet in their ascending stages. There was doul
something in the conditions originating the Onondaga fauna th
adverse to the whole order, while favorable to the corals.

The changes in the brachiopods.—The ubiquitous brachiopods,
d, formed a large constituent of the fauna, both individual a
ific. Many were large and gave evidence of congenial conditio
spirifers (Fig. 208, *d*) and the stropheodonts (Fig. 208, *c*) were t
t characteristic types. The majority of the spirifers, howev
a retrogressive look, in that the fold and sinus were genera

free from plications, as in the earlier types. Some, however, were plicated on the fold and sinus, as were many of the later spirifers and *S. arenosus* (Fig. 207, *e*) of the Oriskany period before. The plications on the sides of the shell of one of the Onondaga spirifers (*S. acuminatus*, Fig. 208, *d*) were sometimes bifurcated, a character that was rare among Devonian brachiopods, but which became common in the Carboniferous period. The loop-bearing shells, which first appeared in the Helderberg, attained an increased importance. The productids, which had been represented in the Niagara epoch by *Chonetes*, were now represented in addition by *Productella* (Fig. 208, *g*), a deep concavo-convex shell with spines scattered over the surface, foreshadowing more definitely than the *Chonetes* the great development of the *Productus* family in the Carboniferous period. The punctate shell, which became an important characteristic in the later Paleozoic faunas, had its first notable development in the Onondaga, where it appears in both the spire-bearing shell, *Cyrtina* (Fig. 208, *e* and *f*), and in the loop-bearing shell, *Cryptonella*. Meristoid shells, which were particularly abundant in the Helderberg fauna, were few in the Onondaga, as were also the orthids, while the pentamerids had dwindled to minor importance.

The notable development of the cephalopods.—The mollusks contributed several very notable features to the fauna. The cephalopods in particular presented characters in striking contrast to those they bore in the Helderberg and Oriskany faunas. It will be recalled that the cephalopods were very meagerly represented in those faunas. In the Onondaga, however, they were present in great abundance in the old types, and in addition, they presented an important new one, the lobate-sutured goniatites (Fig. 208, *l*). It will be remembered that in the primitive types of the cephalopods the septa of the shells were plain, or symmetrically curved, and that the line of juncture with the outer shell was a simple curve. In the goniatites, the septa were abruptly bent and the suture-line lobed, as illustrated in Fig. 208, *l*. This was the first notable step in the flexation of the septa and of their sutures, a character which was to attain remarkable complication in the Mesozoic era. Had this new and divergent type appeared alone after the dearth of cephalopods in the Helderberg and Oriskany faunas, it might have been attributed to the repressive conditions which that dearth seems to imply, but the old forms accompanied n notable abundance, as already remarked. Seventy species o alopods are described from this fauna in New York alone. The particularly abundant in the Schoharie grit (p. 422), which occu the same district and had the same essential characters as th kany sandstone, which had been so barren of cephalopods. The also abundant in the calcareous tracts farther west, thus exhibit their relative independence of bottom conditions, as might b ected of free-moving, predaceous animals. While the orthocera did not reach the gigantic dimensions of their Ordovician prede ors, individually they attained fair sizes, three inches in diam being not uncommon. The club-shaped *Gomphoceras* appeared nany large species, and the curved *Cyrtoceras* and *Gyroceras* were ndant, while the closely coiled *Nautilus* was present but not abun t. The ornamentation of the exterior was a notable feature, but e inferior to the elaborate ornamentation which it foreshadowed. s prolific retention of old forms, combined with the introduction new type, points apparently to some distinctive set of conditions ch distinguished the history of the Onondaga fauna, either in its inating tract, or in its expansional stage, or in both.

The persistence of the previous types of the gastropods and pelecy s.—On the other hand, it is to be noted that the gastropods wer sent in abundance and largely in the same peculiar facies that the assumed in the Helderberg and Oriskany faunas. As there, th ulids were numerous, though perhaps less abundant. The acquisi of spines, which was initiated in the Oriskany fauna, became nounced feature in this (Fig. 208, *h*), and perhaps signified tha e was occasion for defense, an occasion which either the fishe he cephalopods could doubtless have supplied. There were man r forms of gastropods, including *Euomphalus*, coiled in a plan *Murchisonia*, coiled in a very high spire. These, with the ca ped capulids, filled out a full complement of gastropod type re was a notable similarity of the gastropods to those of th derberg and Oriskany faunas, which seems to imply derivatio n them, in contrast with the peculiarities of the cephalopods whic n to imply an origin from some other fauna.

The pelecypods were also abundant and often resembled thos the Helderberg and Oriskany from which many of them we ended. The large oblique-winged aviculids were again conspicu us, and *Conocardium* (Fig. 208, *i*), distinguished by the flattening of one end and the protrusion of the other, reappeared, having been absent from the Helderberg and Oriskany, after being represented by several species in the Silurian.

The revival of the trilobites.—Trilobites were present in more han half a hundred species, a notable increase over the known species of the same region in the preceding epoch. The presence of a remarkable number of highly ornamented species was a conspicuous feature. Spines, nodes, and granulations freely diversified their somewhat rratic forms. The dalmanites led in this decorative movement, hough the species here represented (Fig. 208, *k*) is a modest form. As far back as the Niagara, this genus had shown its ornamental tendencies, but it only reached its maximum display in the Onondaga epoch. Its chief rivals in these lines were the acidaspids and lichads. Other crustaceans were but sparingly represented, the barnacles alone having been found thus far.

Other forms.—Of other types, there were annelids, sponges, hydrozoans, bryozoans, and probably protozoans, all of which played inconspicuous though, in the economy of the whole, doubtless not unimportant parts.

The foregoing sketch has been based essentially upon the aspects presented by the Onondaga fauna as found in the eastern interior basin. In the James Bay region its facies is not well known. Corals were a conspicuous element and the identification of the fauna has been based chiefly on them. Fishes were also present there, a fact to be noted n view of the question of their previous home. No capulids, or gastropods of any kind, have been reported. Their absence may be attributed in part to the smallness of the collections—for the entire absence of gastropods is highly improbable—but their presence in great abundance, as in the Helderberg and Oriskany faunas, is equally mprobable, and the most reasonable conclusion is that the gastropods were but an inferior element in the James Bay fauna, and that the large gastropodous factor of the Onondaga of the interior sea was derived from the Oriskany fauna already in possession of the ground when the succeeding invasion took place. This is supported by the resemblances already noted.

We have no evidence that any of the distinctive species of the Onondaga fauna lived in the South American region, where certain of [illegible] notable abundance [illegible] Several cephalopods are described from the fauna of New York [illegible] were particularly abundant in the [illegible] 420 [illegible] the same district and in the same [illegible] sandstone [illegible] were also abundant in the calcareous [illegible] west, [illegible] their relative independence of [illegible] conditions, [illegible] expense of free-moving predaceous animals. While the [illegible] did not reach the gigantic dimensions of their Ordovician [illegible]cessors, individually they attained large size, three [illegible] being not uncommon. The [illegible] *Gomphoceras* [illegible] many large species, and the curved [illegible] and *Gy*[illegible] abundant, while the closer coiled *Nautilus* was present in [illegible]. The ornamentation of the exterior was a notable [illegible] of the elaborate ornamentation which it [illegible]. The [illegible] retention of old forms [illegible] with the [illegible] of new types points apparently to some distinctive [illegible] which distinguished the history of the [illegible] fauna, originating [illegible] or in its expansional stage, or in both.

The persistence of the previous types of the gastropods [illegible]pods. On the other hand, it is to be noted that the ga[illegible] [illegible] the same [illegible] [illegible] and [illegible] faunas. [illegible] perhaps [illegible] [illegible] the [illegible] fau[illegible] [illegible] Fig. 20[illegible] and perhaps [illegible] for defence, an occasion which eit[illegible] the cephalopods could doubtless have supplied. The [illegible] of gastropods, including *Euomphalus*, coil[illegible] [illegible] coiled in a very high spire. These, [illegible] filled out a full complement of gas[illegible] [illegible] similarity of the gastropods to [illegible] [illegible] faunas, which seems to imp[illegible] [illegible] with the peculiarities of the cepha[illegible] [illegible] some other fauna.

[illegible] were [illegible] abundant and often res[illegible] [illegible] from which many [illegible] [illegible] winged aviculids were ag[illegible]

Oriskany species lived before and where certain of the Hamilt cies lived afterwards. This implies that the Onondaga fauna v distributed in that direction. In the St. Lawrence embayme ich had played so critical a part in the evolution of the Americ eozoic life, the Onondaga fauna appears to have no distinct rep tation. Such traces as are present appear to be only those wh ght arise from the counter-migration of Onondaga tribes into t eding-ground of migrations. There was quite certainly conn with northern Europe, because a notable number of pecul es are common to the two regions.

The whole assemblage of life displayed in this remarkable fau ms to be explicable by postulating a generating tract in the Huds y embayment, or in some more northerly or northeasterly regi sibly on the Eurasian continent. Into this it may be assum t a portion of the Silurian fauna retired, and underwent devel nt by itself. This fauna, after a prolonged evolution in the northe ion, during which the Helderberg and Oriskany faunas were su sively occupying the interior, invaded the eastern interior s on entrance, this fauna in part displaced and in part comming h the Oriskany fauna which then occupied the ground. So gering representatives of the Helderberg fauna were probably a sent. This admixture of exotic and indigenous forms, evolv ether under the congenial conditions of the interior sea, develo later phases of the Onondaga fauna.

The Southern Hamilton Fauna.

The life which occupied the eastern portion of the interior ing the earlier part of the Hamilton epoch will be best underst calling again to mind the geographic changes which permitted rance of a new factor from the south and controlled the devel nt of the whole. There appears to have been a warping of the e by which the land at the northeast was gently lifted and its ri uvenated, so that they bore much more silt into the basin t ore, and this, spreading widely over the bottom, changed the dep m limestone to shale in that part of the basin, while the format limestone continued as before in the western portion. This wa movement may have been accompanied and abetted by clim vegetal conditions favorable to silt wash. The warping app to have gone so far at length as to close the eastern straits through which the Helderberg and Oriskany faunas had entered. In the southwestern region the warping was downward and permitted the sea to creep out upon the previous land, as shown by the overlap of the Hamilton formation. There is no positive stratigraphic proof that this went so far as to make a connection with the ocean in that direction, but this seems highly probable. It is quite obvious from the nature of the life that an oceanic connection was maintained somewhere, and there is an absence of evidence that it was maintained either to the northeast or to the north, for no Hamilton beds are found in those directions, nor are there any faunal indications of such a connection. On the other hand, the fauna contains peculiar forms found also in South America, and this fact, together with certain features of distribution within the interior, strengthens the presumption of a connection lying somewhere in the lower Mississippi tract. Unfortunately this region is very deeply buried beneath younger deposits, and a stratigraphic demonstration of the continuity of the Hamilton sediments through the supposed strait is impracticable.

Assuming that these were the physical conditions which led to its introduction, the earlier Hamilton fauna may be regarded as the result of a resident clear-water fauna contending with increasing turbidity of water on the one hand, and with the invasion of a southern fauna on the other. It involved the domestic modification of the resident fauna to fit new conditions, and the absorption and accommodation of foreign accessions, for the latter do not seem to have overpowered the former. It was not therefore so radical a transformation as that which attended the introduction of the Onondaga fauna, when the invaders were not only the master type, but were aided by a progressive physical change in their favor.

The progress of the sharks and arthrodirans.—The relics of Hamilton fish thus far recovered are less numerous than those of the previous epoch, and, like them, are largely fragmentary, but they indicate an advance in structural development. The arthrodirans reached their climax in massiveness and distinctive characters. The *Dinichthys herzeri*, the leading type, was one of the largest and most formidable fish known, with an estimated length of 20 feet, and very massive proportionately. It was armed with formidable mandibles two feet in length, which, in lieu of teeth, were developed into shear-like and beaked

:ing edges that closed upon their fellows in much the way the man-es of a turtle do. These are illustrated diagrammatically in Fig. 209. forward portion of the body was encased in heavy armor-plates, ng great defensive as well as offensive power. Related types of formidable aspect are also known. The sharks are most commonly resented by their teeth and highly developed fin-spines, some of latter reaching a foot in length. In both classes the implements varfare make up nearly the whole record, and this doubtless cor-ly implies the dominant state of affairs in the vertebrate kingdom.

The decline of the corals.—The corals of the Onondaga fauna lived in some notable measure and constituted an element in the new na. They were adversely affected by the increased turbidity of waters, and retired largely to the western part of the basin and lined greatly in importance.

The advance of the crinoids.—The *Echinodermata* were somewhat ter represented, crinoids, cystoids, blastoids, and asteroids being sent, though not generally prolific. Locally the crinoids must e been abundant, for certain limestone beds are largely composed crinoidal remains. The Hamilton genera were usually the same those of the preceding Onondaga epoch, but not a few additional s appeared, a foreshadowing of the remarkable crinoidean develop-t of the early Carboniferous period. A very peculiar form was *Arthroacantha* (Fig. 210, *q*), which was furnished with movable spines ed miscellaneously over all the plates of the dorsal cup, and attached he calyx by means of a ball-and-socket joint like the spines of the -urchins, an obvious case of parallel evolution. The cystoids reappear eebleness in the single genus *Agelacrinus*. The blastoids increased ir representatives notably, some species being similar to those of Onondaga, while others, as the *Pentremitidea*, approached the type the Carboniferous pentremites. One of the most peculiar of the stoids was the irregular *Eleutherocrinus* (Fig. 210, *o* and *p*), which unlike any earlier member of the group. Some finely preserved fishes have been found, but they were not abundant. They fol-ed the Paleozoic type in those features in which the later forms er from the earlier.

The climacteric deployment of the brachiopods.—The brachiopods, to their persistent nature, held an important place in this fauna before. They were no less numerous individually or specifically;

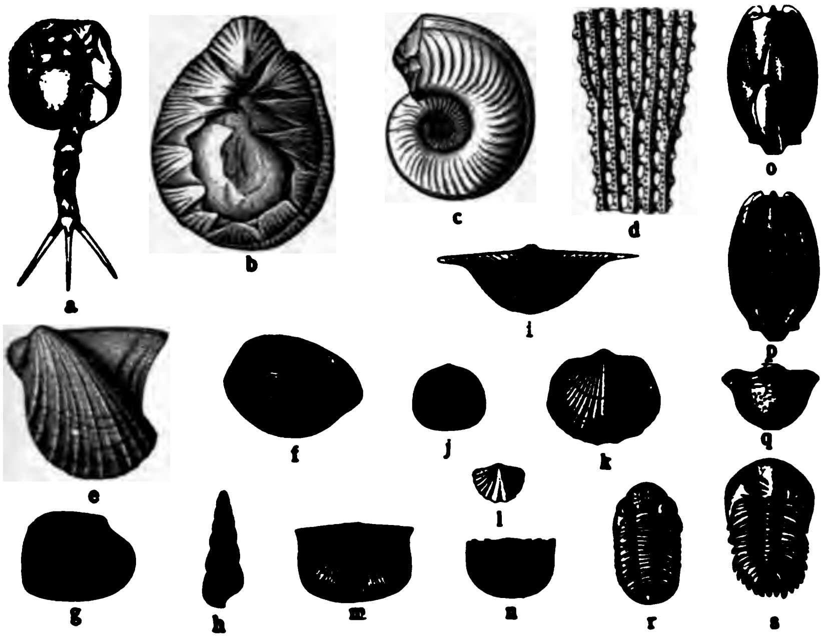


FIG. 210.—THE HAMILTON FAUNA. *Crustacea: a, Echinocaris punctata* (Hall), one of the phyllocarid crustaceans, a group more highly organized than the trilobites; *b, Protobalanus hamiltonensis* Whitf., a sessile cirriped; one of the earliest representatives of these degenerate crustaceans. *Cephalopoda: c, Goniatites vanuxemi* (Hall), one of the goniatites which become more numerous in this fauna. *Bryozoa: d, Fenestella emaciata* Hall, one of the fenestelloid forms which became very abundant in the Middle Devonian faunas. *Pelecypoda: e, Pterinea flabella* (Con.); *f, Palæoneilo constricta* (Con.), and *g, Cypricardella bellistriatus* (Con.); three of the common forms of pelecypods in the Hamilton fauna. *Gastropoda: h, Loxonema hamiltoniæ* Hall, a high spiral shell of a form not uncommon in this fauna. *Brachiopoda: i, Spirifer pennatus* (Atw.), one of the long-hinge-lined spirifers more conspicuous in the Middle and Upper Devonian than elsewhere; *j, Rhipidomella vanuxemi* Hall, one of the orthid genera which has its great development in the Devonian; *k, Tropidoleptus carinatus* (Con.); *l, Vitulina pustulosa* Hall, and *m* and *n, Chonetes coronatus* (Con.), three peculiar species of brachiopods in the Hamilton fauna. They have their closest relationships with South American, Middle Devonian species. *Echinodermata: o–p, Eleutherocrinus cassedayi* S. and Y., a peculiar, irregular blastoid whose form has been modified by the loss of its column and its pentamerous symmetry. During life it probably rested upon one side on the sea-bottom; *q, Arthroacantha punctobrachiata* Williams, a peculiar genus of crinoids restricted to the Middle and Upper Devonian faunas. It is characterized by the presence, on the plates of the calyx, of movable spines similar to those on the sea-urchins. *Trilobita: r, Phacops rana* (Greene), the most common trilobite of the Hamilton fauna. The genus, although present in the Silurian, has its great expansion in the Devonian; *s, Cryphæus boothi* Greene. This is one of the last of the dalmanites. Note the serrated margin of the tail, and compare with Figs. 208, *k*, and 203, *u*.

d their climax of deployment lies somewhere here. Their curv
o broad that its highest point is not easily fixed with exactness
many respects the brachiopods of this fauna were closely allie
ose of the Onondaga and many species passed unchanged fron
arlier into the later fauna. In most cases the changes in th
onment were paralleled by changes in form that rose to specifi
. The lowly inarticulate brachiopods still persisted as a mino
r, while the more highly differentiated forms attained wide diver
and high rank. The stropheodontas retained about the sam
ive place, waning somewhat perhaps in size, though still ofte
. The spirifers reached a climax in the extension of their hinge
(Fig. 210, *i*). This extension is particularly characteristic c
Hamilton epoch, though a feature of the Devonian generally
geological series perhaps presents no simpler or more obtrusiv
acter by which a formation may be identified than these excessivel
d-winged spirifers. Some specimens had a breadth along the hing
four or five times as great as the length of their shells, if breadt
be said to be greater than length in any case. The *Orthis* famil
so prominent, had fallen to a very subordinate place. The pr
ids increased notably, and were obviously advancing towa
great expansion in the Carboniferous period. The meristoi
away and were nearing the close of their career. The loop-beare
he *Terebratula* and *Cryptonella* types increased. The persiste
nchonella family was represented by species wonderfully proli
dividuals. The pentamerids made but a feeble showing. Seve
ies of extreme interest and significance invite special notice, amo
h are *Tropidoleptus carinatus* (Fig. 210, *k*), *Vitulina pustulo*
. 210, *l*), and *Chonetes coronatus* (Fig. 210, *m* and *n*). The fi
belong to peculiar genera not previously found in the interi
n. Apparently they could not have been derived from any
preceding inhabitants of the region. The third species belong
genus represented by other species that previously lived in t
on, but this particular species is peculiar, and does not give sig
ny near kinship to the previously resident members of the gen
these forms were locally abundant in the Hamilton assembla
y bear the marks of immigrants, however, and a search for th
ner home and relatives reveals the fact that in South Ameri
same species, or closely allied ones, lived in abundance, and th

they are there preserved in beds which overlie beds containing Oriskany forms. This means that they lived in South America at a time just previous to or nearly identical with their appearance in the North American fauna. That they were immigrants from the south is the almost necessary inference.

The advance of the cephalopods.—The mollusks were an interesting factor of the Hamilton fauna. The new lobate-sutured cephalopods, the goniatites, which were represented by a single known species in the previous fauna, now appeared in six species. One of these, *Goniatites vanuxemi* (Fig. 210, *c*) reached the notable size of a foot in diameter. The *Nautilus* regained the prominence it had lost since the Niagara epoch and appeared in forms rivaling the large goniatites, and some of them began to exhibit the node-like ornamental expansions of the shell which became so conspicuous in the later Carboniferous faunas. It seems to have replaced the more loosely coiled *Cyrtoceras* and *Gyroceras* of the previous fauna. The straight forms were present and were closely allied to those of the Onondaga epoch.

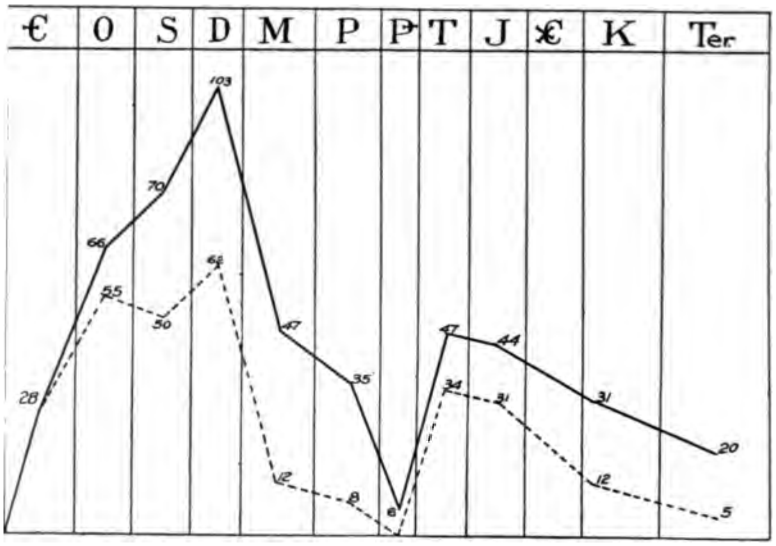
The abundance of the pelecypods.—The silty bottoms favored the pelecypods, and they developed in great abundance, the number of recognized species approaching 200. The aviculids of the obliquely winged type were the most conspicuous and characteristic. A representative form is illustrated in Fig. 210, *e*. A part of the pelecypods were obviously derived from Onondagan predecessors, while others were peculiarly Hamilton types, either immigrants, or forms so widely different from Onondagan forms that their parentage is unrecognizable.

The subordinate place of the gastropods. —Though fairly abundant, the gastropods were quite inferior to the pelecypods in numbers. The genera were almost entirely the same as in the Onondaga epoch, though the species were largely new. The capulids were still abundant, but by no means so plentiful as in the preceding faunas. The pteropods, again on the ascendant, were represented by *Conularia*, tentaculites, and a minute *Styliola* which largely formed certain thin beds of limestone, as the tentaculites had previously done.

Other features.—The Hamilton trilobites differed notably from the Onondagan in being much inferior in numbers and much less ornamented. The dalmanites was present, but in relatively modest garb. As an offset, the other crustaceans were more amply represented by the phyllocarids (Fig. 210, *a*) and cirripeds (Fig. 210, *b*). Among the r were the first known barnacles of the modern sessile type. In g its pedicel, and in fixing itself immovably on other objects, it me a degenerate type, but it found an unworthy place for itself hich it has hung with wonderful persistency, not unlike the debased an class which it has come to typify, for it has lived through all ıges since, and still shows no signs of extinction.

The Northwestern Hamilton Fauna.

Vhile the preceding fauna was developing in the eastern interior ınd apparently receiving contributions from more southerly coasts, her fauna was evolving on somewhat different lines in a sea that



211.—This curve is compiled chiefly from data contained in Schuchert's Synopsis of American Fossil Brachiopoda, and represents approximately the state of our present knowledge of the geologic range of the genera of fossil Brachiopoda. The broken line represents the number of new genera initiated during he successive geologic periods; the full line represents the total number of genera present; and the difference between the two represents the number of genera which have passed over from the preceding period.

ears to have overspread a large tract in the northwestern interior. sea embraced portions of Missouri, Iowa, Manitoba, and the kenzie valley. It doubtless had its oceanic connection at the h or northwest. It does not appear to have had any connection the ocean to the south in the earlier stages. It seems to have

adually extended itself to the southward and at length to have joined
e eastern sea across the tract stretching from the old lands of Wis-
nsin to the similar old lands of Missouri which had in the earlier
ges formed a separating isthmus, but which at length became sub-
erged by the advance of the seas on either hand. This northwestern
una was closely allied to the Middle Devonian fauna of eastern and
ntral Europe. So close indeed is the similarity that the inference
forced that there was free intercommunication between the two
gions. The prolonged sea-arm that reached down the great interior
lley of the northwest was perhaps no more than an *eastern* exten-
on of the Eurasian Middle Devonian province.[1] The extension of
is great sea-arm took place late in the Devonian period, for the
rata bearing its peculiar life lie directly on the older formations in
issouri, Iowa, and Minnesota, with no Lower Devonian beds between,
owing that the sea crept in after the earlier Devonian epochs had
ssed. The brachiopods furnish the most decisive evidence respect-
g the relations and genesis of this northwestern fauna.

Brachiopods as evidence of geographic connections.—In Europe there
a horizon so well marked by *Hypothyris* (*Rhynchonella*) *cuboides*
at it is known as the "cuboides zone" and has a notable place in
e literature of the subject under that name.[2] This species also occurs
eastern Asia (China), in northwestern America (Mackenzie valley),
western America (Great Basin), and in the American interior, as
r east as New York. To show how well the peculiarities of this
rm are held through this wide distribution, figures of typical indi-
duals from England (Fig. 212, *h*), Russia (Fig. 212, *f*), China (Fig. 212,
, the Great Basin (Fig. 212, *i*), and New York (Fig. 212, *e*) are
ranged side by side. Their close similarity is very notable. *Spiri-*
disjunctus is another brachiopod of similar range, illustrations of
ich from England, China, Mackenzie valley, and New York are
ranged for comparison (Fig. 212, *a*, *b*, *c*, and *d*). *Schizophoria* (*Orthis*)
iatula is still another species common to Europe, Asia, and different
rts of America, and is illustrated by specimens from England, China,
ackenzie valley, Nevada, Iowa, and New York (Fig. 212, *j*, *k*, *l*,
, *n*, and *o*). *Gypidula comis* from Iowa and China is illustrated by
g. 212, *p* and *q*, and *Spirifer tullius* by specimens from New York

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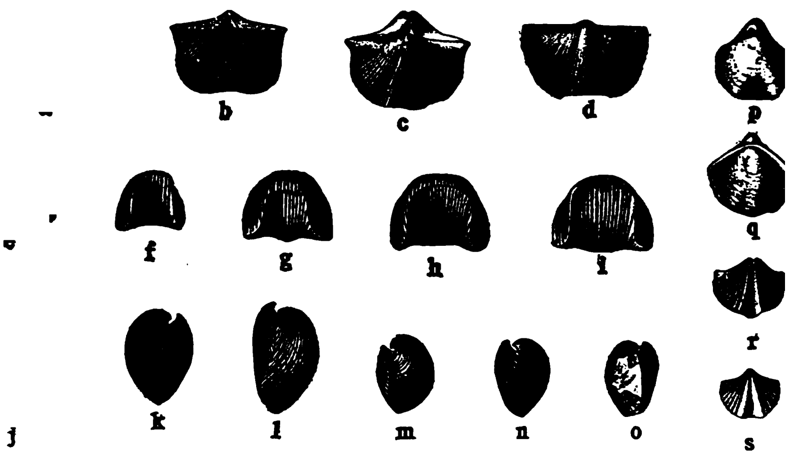
[1] Weller, Journ. of Geol., Vol. VI, p. 306.

[2] Williams, The Cuboides Zone and its Fauna. Bull. G. S. A., Vol. I, p. 481, 1890.

Mackenzie valley (Fig. 212, *r* and *s*). These strikingly illustra
community of this wide-ranging fauna, and its close approa
cosmopolitan fauna. Now none of these species had any repr
ıtive at all closely allied to it in the southern Hamilton, nor a
ɜ any species in it from which these forms could probably ha
derived. On the other hand, allied forms have been found i
land, Belgium, France, Germany, Russia, Persia, and China. Th
ıs to make it clear that the derivation was from that quarte
that, while the American northwestern fauna had close connectic



212.—Upper Devonian Brachiopoda, showing the geographic distribution
e species: *Spirifer disjunctus* Sow.; *a*, England; *b*, China; *c*, Mackenzie vall
New York. *Hypothyris cuboides* (Sow.); *e*, New York; *f*, Russia; *g*, Chi
England; *i*, Great Basin. *Schizophoria striatula* (Schl.); *j*, Mackenzie vall
New York; *l*, England; *m*, China; *n*, Iowa; *o*, Nevada. *Gypidula comis* (Owe
Iowa; *q*, China. *Spirifer tullius* Hall; *r*, New York; *s*, Mackenzie valley.

the Eurasian continent, it had no previous migratory relatio
the eastern and southern Hamilton province. This is furth
ıgthened by the fact that while the latter had species of Sou
rican origin, none of these latter are found in the northweste
a previous to the joining of the two provinces at the close of tl
ɜ. Wide-ranging as both the Hamilton faunas were, they h
yet entirely escaped from provincial limitations.

he corals of the northwestern Hamilton fauna were of the Ono
type, which seems to indicate that at an earlier stage the Ono
fauna and the ancestors of the northwestern Hamilton fau
ɜ into communication, as might well have happened from tl

northern distribution of both. The corals of the northwestern Hamilton fauna were more abundant than those of the southern Hamilton fauna, but much inferior to those of the Onondaga.

The echinoderms were a minor factor, as were also the trilobites and bryozoans. The pelecypods were less abundant than those of the southern Hamilton and different from them. Gastropods were present, but not important, and the same may be said of the cephalopods.

Some notable fish remains have been found in Iowa, but they are quite different from these of the eastern area, although perhaps derived from them by westward counter-migration, after the communication between the provinces was established.

In the later part of the Hamilton epoch, when the southern and northwestern seas became confluent, the northwestern fauna invaded and overran the eastern and southern territory, and a new fauna developed from the commingling of the members of the two. This leads on to the closing, more cosmopolitan phase of Devonian life in the interior sea, the Chemung fauna.

The Later Devonian (Chemung) Fauna.

The commingling and conflict which attended the invasion of the eastern and southern interior sea by the northwestern fauna may be regarded as the initial and controlling event in the evolution of the Upper Devonian fauna. As in the case of the Onondaga invasion, the northern fauna proved the more virile and gave character to the composite fauna that resulted from the extinction of the weaker species and the fusion of the remaining invaders and invaded. The stratigraphical evidence of the invasion is first caught on the western border of the invaded sea in the fauna of the Hamilton at Milwaukee. The northwestern invaders appear first in the eastern part of the basin in the Tully limestone of New York, where the detection of the significance of the fauna is due to the critical studies of H. S. Williams.

The influence of faunal and physical conditions.—From the fact that the sediments of the time were predominantly silts and sands, only a slight and precarious submersion of the occupied portions of the continental platform is inferred, and this was not a condition altogether favorable to the evolution of a general fauna of the first order, and the local conditions were effectively impressed on the fauna. In the interior basin there were three dominant factors: (1) the resisouthern Hamilton fauna, (2) the invading northwestern faun (3) the shallow and rather turbid waters in which these faun and merged.

he last of these factors expressed itself in a notable rarity of cora hich the impurity of the waters was uncongenial. In a less ee, this was true of the crinoids, but they none the less exhibit er surprising powers of resistance or of adaptation, since all t rs were represented. Cystoids and blastoids have not been foun starfishes were rare. The first known American echinoid appear he Chemung, though in Europe the type had appeared as ear e Ordovician.

he brachiopods best express the outcome of the commingling resident and immigrant faunas. They distinctly indicate t ps: (1) an indigenous class which had developed from the pr ng resident fauna of the basin; and (2) an exotic class whic derived from the immigrants and bore European character ng those of native descent were *Atrypa reticularis*, *Atrypa hystri* *ina hamiltonensis*, *Tropidoleptus carinatus*, and probably certa ies of *Stropheodonta* and *Productella*. Among the prominent imm ts were those previously discussed and illustrated in Fig. 21 foreign group was more conspicuous than the native. The revers ever, was the case with the mollusks. The pelecypods were nume but not so abundant as in the preceding epochs. The majori ar to have been descendants of the resident bivalves. Distin ign relationships have not as yet been satisfactorily distinguishe gh some suggestive resemblances have been noted. Perha bivalves were not well suited to distant migration. The gast s were less numerous than before, and apparently local. T opods were represented by *Tentaculites* and *Conularia*, similar e of the preceding faunas. The genera of the cephalopods we lly the same as those of the southern Hamilton, though the spec mainly new; but in the goniatite genus *Manticoceras*, which ly characteristic of certain Portage beds in western New York, th a conspicuous Eurasian immigrant element from the northwe otable as that of the "cuboides" fauna.[1]

The marine fishes of the late Devonian are not very abundan resented in present collections, and can only be characterized wi

[1] J. M. Clarke, 16th Ann. Rep. N. Y. St. Geol. for 1896, pp. 22–161.

ome reserve. They seem to have been of the same general types as in the preceding epoch, but with a decline in the singular arthrodirans, an increase in the sharks, and a continuation of the ganoids without assignable change.

The pelagic and abysmal life of the Devonian.—Concerning the pelagic life of the Devonian nothing is known except as it may be obscurely suggested by the floating forms that were entrapped in he sediments of the shallow-water zone, or that found their way into he interior seas, and this element does not admit of satisfactory interpretation.

Respecting the abysmal life nothing is known. The strata reveal no clear case of beds laid down on the abysmal bottom of the Devonian ocean and subsequently lifted to an accessible position. It is therefore mportant to keep ever in mind the limitations to which all statements especting the marine life of this period, if not of all geological periods, are subject.

Marine vegetation.—As usual, the record of the marine plants is oo imperfect for satisfactory discussion. There are evidences of lgæ as before, and they appear to have been well deployed, and theoetically they must have been abundant. Sections of what are interpreted as the stems of a gigantic seaweed (*Nematophycus*), sometimes eaching three feet in diameter, have been found. They perhaps mark he dimensional climax of this form.

The Devonian Fauna in the Great Basin Area.

In the region which constitutes the Great Basin of the west, a arge area seems to have been occupied continuously by the sea from bout the beginning of the Devonian time to the later part of the Carboniferous period. It seems to have been measurably free from both the physical and the biological changes which gave such diverity to the eastern provinces. The fauna seems to have had a slow ontinuous evolution, fed, it would appear, from time to time by accesions from the two northern provinces or from some source with which hey were connected. None of the distinctive South American forms ppeared in it, nor any of the peculiar Helderberg or Oriskany forms. t is inferred, therefore, that it was disconnected from these provinces hroughout the whole Devonian period. On the other hand, a nota-

number of species were common to it and to the northwestern
vince, as also to the interior province after it had been invade
the Onondaga and northwestern Hamilton faunas. While it
na is not yet well enough known to sanction the drawing of fina
clusions, it bids fair to offer as fine an example of a stead
nterrupted development of a provincial fauna as does the eastern
vince of the fluctuating and militant development of a composit
na out of provincial invasions.

The western fauna has, as now known, few salient features. Th
ils which were present in considerable abundance were largel
ntical or closely allied to those of the Onondaga fauna of the north-
, and doubtless had a common origin, through some northern
nection. Brachiopods were, as might be expected, the leadin
nent. Several species were identical with those of the Onondag
na, and several were identical with species embraced in the north-
tern Hamilton fauna. The former are found mainly in the lowe
zons of the formation, and the latter in the upper. In this the
n to indicate an early communication with the sources of the Onon
a fauna and a later connection with those of the northwestern
nilton. There were some pelecypods also that held a like rela
, but the greater number seem to have been indigenous. Alto
er they were rather abundant. The same may be said of th
ropods. The cephalopods, so far as known, were few and mostl
genous. The trilobites were feebly represented and were prob
all indigenous. Echinoderms have not yet been reported. Fis
ains are found abundantly in certain localities.

II. The Life of the Land Waters.

Principle of interpretation.—It would doubtless be as difficult
w any sharp line between the fishes of the land waters and tho
he sea in Devonian times as it is now, even if we had as comple
wledge of them, probably even more so, for the differentiati
he two classes was doubtless less complete than now. For ge
cal purposes, however, all those fishes that were denizens of t
ams and lakes, also those of the freshened waters of the estuari
s, and inlets on the land border, may be classed together as fish
he land waters, for they were dependent on conditions inseparab

from the land. It may fairly be assumed that when land plants, insects, and terrestrial mollusks are present in relative abundance, and true marine forms are absent, the associated fishes are land-water forms. When land plants, insects, terrestrial mollusks, and fishes are mingled with a limited selection of species that are usually marine, but which may have frequented somewhat freshened waters, the better inference is that the mixture took place in brackish waters largely surrounded by land from which the true land forms were floated in. When land plants, insects, etc., are commingled with a full group of true marine forms, the better inference is that the former were carried out to sea by floods, and that the deposit was really marine. In such an association no safe inference can be drawn relative to the habitat of the fishes, unless there is independent evidence, for they may have been true dwellers in the sea, or may have been floated out from the land streams. If these three cases occurred alone, the interpretation would be fairly easy; but it so happens that in some of the great Devonian series, certain parts of the formation embrace cases of the first or second class, while in other parts cases of the third class are presented. The better inference here is that the formation took place in part on land or in land waters, and in part in marine waters. The deposits forming to-day in the great valley of California embrace fluvial, lacustrine, and marine deposits, together with land aggradation. At a geologically distant day, only small portions of this aggregate would probably be found fossiliferous, and the evidences of these portions might be quite opposed to one another, according to the particular parts selected; but the true interpretation is obvious. This appears to be very much the state of things that is recorded in the " Old Red Sandstone " type of the Devonian deposits. In America, the Catskill deposits, or some large part of them, appear to belong to this type. It is clear that they were contemporaneous with the Chemung in part, and the opinion of Williams and others that in their total range they may even have been contemporaneous with the whole of the marine Devonian series is inherently reasonable, for there can be little doubt that there were lacustrine, fluvial, and land-aggradational deposits at all times throughout the period. The only question is whether these have been preserved and are now known. In the Canadian provinces, deposits of this kind seem to have a quite ample development. But as all these deposits were,

)y hypothesis, laid down in more or less local basins, no exact correla-ion of them is possible at present and they may best be considered ogether. The general faunal conception is therefore that in the ppalachian tract and in the Canadian provinces lying to the north-ast of it, as well as in Great Britain and Russia, there were many odgment basins that were progressively filled by land-wash and fresh-vater sediments, and that these basins were the home of a fresh-water r brackish-water fauna, in which ostracoderms and fishes were the eading elements, and crustaceans their chief colleagues.

The remarkable deployment of the crustacean-ostracoderm-verte-rate group.—No more suggestive combination of ancient life is pre-ented by the geological record than that which is found in these upposed fresh-water deposits. The type was foreshadowed by the urypterids and fishes, or fish-like forms, that appeared in the closing tages of the Silurian, but the record of that time is too imperfect o disclose its deeper significance. Even with the much superio naterial of the Devonian period, the more profound significance i nly just beginning to be realized. The center of interest is a uniqu roup of ostracoderms, which were at first interpreted as placoderm

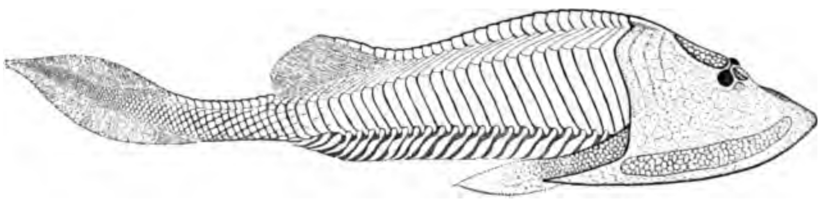


FIG. 213.—Restoration of *Cephalaspis* seen from the side. (After Patten.)

ishes, and later classed with the jawless fishes (*Agnatha*, lamprey tc.), but which seem now to be clearly proven[1] to be an entirely di inct class lying between the arthropods and the vertebrates, a aving some of the characteristics of each, but not truly belongi o either. Their supreme interest lies in the force they give to t uggestion that the vertebrates sprang from the arthropods.

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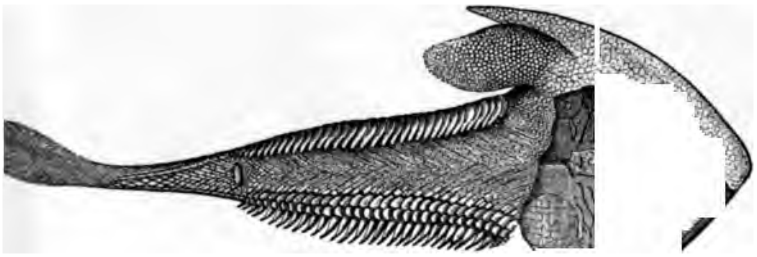
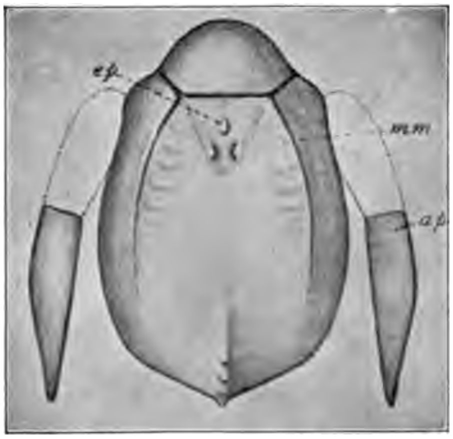
[1] W. Patten, On the Origin of Vertebrates, with special reference to the structu f the Ostracoderms. International Zool. Cong., Berlin, 1901. On the App ages of *Tremataspis*, Am. Nat., XXXVII, 1903, p. 223. On the Structure of t *Pteraspidæ* and *Cephalaspidæ*, Am. Nat., XXXVII, 1903, p. 827. New Facts c erning *Bothriolepis*, Biol. Bull. No. 2, 1904, p. 113.

ostracoderms.—The strange forms grouped under this term cternal resemblances in the head and trunk to the trilobites



.—Restoration of *Cephalaspis* seen from below. A part of the ventral wall e head is shown on the left, the rest being removed to show the inner surface e roof of the shield. (After Patten.)

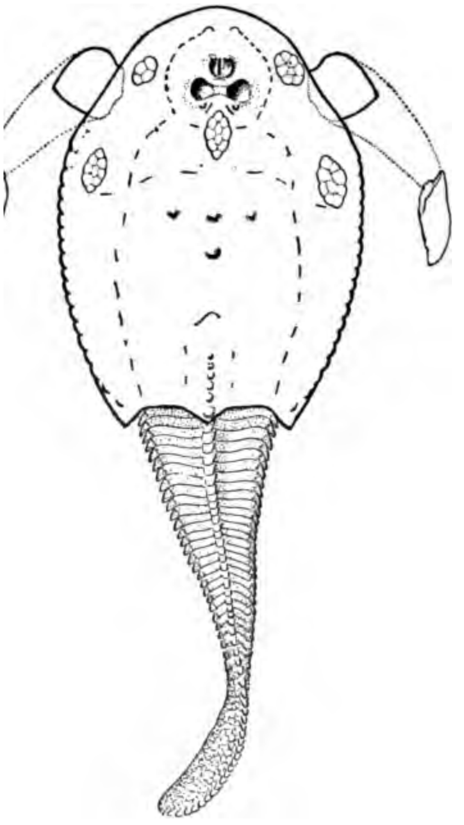
g-crabs, while some of them have caudal fins and a fish-like Because of these last features and the presence of bone cells



.—Restoration of the head shield of *Cyathaspis*, showing the oar-like appens, *ap*, the three median eye-pits, *ep*, and the paired muscle markings, *mm*, etimes regarded as gill-pouches. (After Patten.)

dermal armor of some members of the group, as well as their e association with true fishes, they have been classed as fishes ecently. But no vertebræ nor notochord has been found, nor ectoral or pelvic appendages, nor do they possess either upper lower jaws of the vertebrate type. On the contrary each jaw con- s of two separate parts which act upon one another, not verti- ly, in vertebrate fashion, but *laterally*, as in arthropods. This is ecially true of the upper jaw. While perhaps they should remain ler the broad mantle of the term *Chordata*, they must apparently removed from the true vertebrates to a new class.

The forms which show most strikingly the arthropodian anterior l the vertebrate-like posterior, are the cephalaspids (head-shield) strated in Figs. 213 and 214, restorations by Patten. The broad shovel-like head, with the eyes close together on the central ridge, is interpreted as an adaptation to plowing in the mud, half-buried, after the fashion of the modern king-crab (*Limulus*), to which the cephalaspids are believed to have borne more than a superficial resemblance. The eyes were protected by a thin coating of hard material continuous with the outer layer of the shield. The large, segmentally arranged trunk-scales, the tail and the fins, are decidedly fish-like, while the projecte side angles of the shiel (*cornua*), so trilobite-like i aspect, as well as the cephali appendages, are curious fea- tures that have awakene much discussion; as have als the fringing appendages alon the side of the body.



. 216.—Reconstruction of the head and trunk f *Trematapis*, seen from above. Natural ize. (After Patten.)

The *Pteraspis*, the earlies of these curious creatures t ear in America (Salina), is still imperfectly known and the subjec pronounced differences of interpretation. The *Cyathaspis*, Fig. 215

red to this family, seems to throw much light on its relations in it possessed oar-like appendages, median eye-pits, and muscunarkings that assist in interpreting doubtful features in the *Pteraspis*. The *Tremataspis*, as interpreted by Patten, had a broad oval shield, a pair of oar-like swimming appendages, and a relatively small, er slender trunk, as illustrated in Fig. 216. As in the *Cephalaspis*, lateral and median eyes and the olfactory pit were close together he median line, well back from the front margin.

Perhaps the most curious of all these strange creatures were the ichthyds (winged fish), of one of which, *Bothriolepis*, an elegant oration by Patten is shown in Fig. 217. In this the structure been worked out in great detail from a large collection made in Brunswick. The *Bothriolepis* had a short head with close-set ral eyes on movable stalks, an angulated buckler, and a very slender ed trunk bearing two dorsal fins, and a tail of peculiar form. Three on the inner surface of the head, between the lateral eyes, indithe presence of a trioculate median eye. There is no sign of ebræ or of notochord, though the latter may have been present. y anatomical features suggest relations to the arthropods on one side, and to vertebrates on the other.

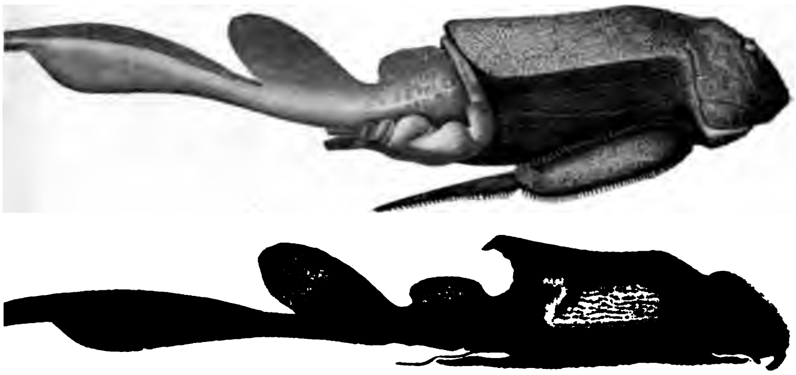
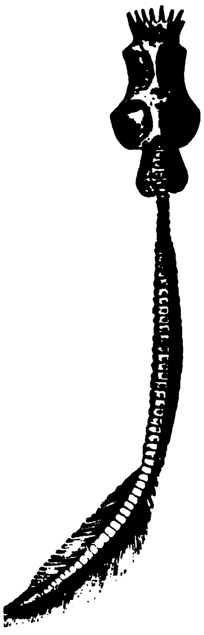


FIG. 217.—Reconstruction of *Bothriolepis*, side view. (After Patten.)

It is obvious from even the few features here noted that the ostrarms differed greatly among themselves, and were probably already ancient widely divergent line. Their distinct separation from fishes puts a new phase on their place in the life series. Instead

ɔeing initial vertebrates, they formed the climax and almost t
of their own strange race, for they practically disappeared wi
period. Their disappearance is not surprising in view of tl
elopment of powerful fishes, for the ostracoderms were obvious
a masterful race. Besides being small, their forms were clum
he main, their locomotive organs lacked flexibility and efficien
orm, and their mouth-parts were weak, and poorly situated f
:essive service, as were also their eyes. They probably plowe
soft bottoms of the sluggish waters, half-buried in the mud, abo
which little beside their peculiarly placed ey
and the backs of their plated bucklers wer
habitually exposed. They flourished in th
fresh waters of the eastern Canadian province
as also especially in England, Scotland, Wale
and northwestern Russia. With little doub
there was a migratory zone between these re
gions. While the ostracoderms are sometime
reported as occurring in beds with marine fos
sils, there is little evidence that they were tru
dwellers of the open sea.

The cyclostomes.—Another strange class c
organisms related to the fishes, but not tru
fish, was represented by the singular littl
lamprey-like form, *Palæospondylus* (Fig. 218
which has awakened much interest because
the suggestion that it was really an ancestr
lamprey, a suggestion supported by many
its characters; but opinions differ as to tl
real nature of this relationship. However th
may be, the vertebrate idea is represented
great simplicity; a slender column of vertebr
lified at one end into a head and finned at the other for a ta
ıout ribs, or paired fins, or any suggestion of paired liml
:e up the known structure. It seems to represent a quite prin
type of the vertebrates. The little creature was scarcely t
ıes long, and so far as known was represented by a single speci
·, found at Achanarras, north Scotland.



218.—*Palæospondylus
nni*, restored by Tra-
ıair; from the Old Red
.ndstone, Caithness,
otland. (After Dean.)

The wide deployment of the fishes.—The true fishes found in t upposed fresh-water deposits of the Devonian exceed in number nd variety those found in the contemporaneous marine formations. Their relative abundance, however, changed notably during the succeedng periods until the sea fishes came to preponderate over the fresh-water fishes. Some of the leading types seem to have flourished in he fresh waters, while it is doubtful whether or not they had any real epresentation in the sea, though their remains are occasionally found n marine deposits. This is of interest in connection with the question f the original habitat of the vertebrates, a question to which the new views of the ostracoderms give fresh point.

Perhaps the strangest of the fishes were the arthrodirans repreented by *Coccosteus* and its allies, Fig. 219. The *Coccosteus* was well protected by plates upon its head and shoulders but not on its poserior parts, of which little is known. The relations of the arthrodirans to other forms are puzzling, but most paleontologists regard hem as a specialized and rather divergent branch related to the ancesors of the lung-fishes.

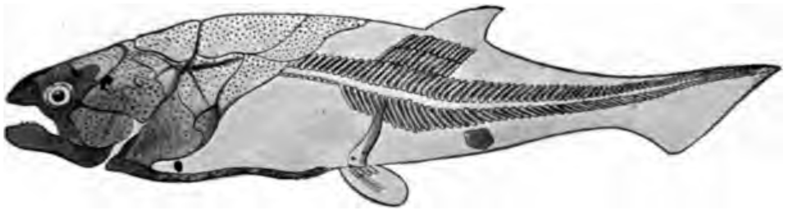
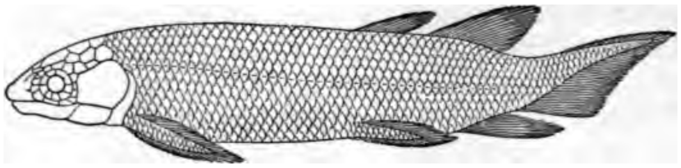


FIG. 219.—A partial restoration of *Coccosteus decipiens;* from the Old Red Sandstone of North Scotland. (After Woodward.) About one-fourth natural size.

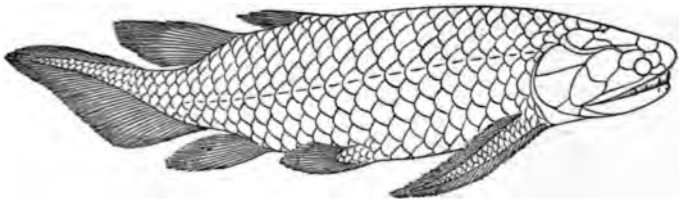
The lung-fishes (*Dipnöi*) formed a notable feature in the fauna. This was perhaps even the time of their maximum development and pecialization. It is a matter of interest that they were more abundant n the fresh-water faunas than in the marine, as it is in line with the act that they are now wholly confined to fresh waters, being repreented by a few strangely isolated forms, viz., *Ceratodus* in Australia, *Protopterus* in Africa, and *Lepidosiren* in South America. The *Dipterus* (Fig. 220), a representative form found in the Old Red Sandstone of north Scotland, had the outlines of a typical modern fish and was completely covered with scales.

The *crossopterygians* (fringe-finned ganoids), at present the most favored claimants to the parentage of the amphibians, were repre-ed by *Holoptychius*, *Eusthenerpteron*, and their allies. These show ıy resemblances to the amphibians in their teeth and skull-bones,



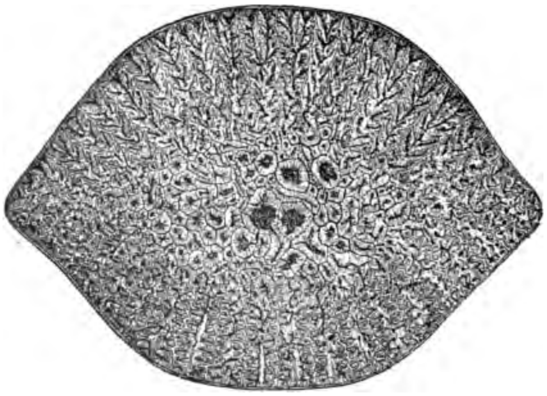
220.—*Dipterus valenciennesi*, restoration by Traquair; from the Old Red Sandstone, North Scotland; about one-fifth natural size.

these structural resemblances of the hard parts count for more ı the physiological resemblances between the lung-fishes and the hibians. In the *Holoptychius* (Fig. 221) the enamel of the teeth



221.—Restoration of *Holoptychius flemingi* by Traquair; about one-eighth atural size; from Old Red Sandstone, Dura Den, Scotland. (After Woodvard.)

intricately infolded, giving a dendritic structure in cross-section, llustrated in Fig. 222, which much resembles the labyrinthodont



222.—Cross-section of tooth of *Holoptychius*, much magnified. (From Smith-Woodward, after Pander.)

ıcture of certain of the early amphibians. The holoptychians ear to have been rather rare in the early Devonian, but to have been dominant forms in the latter part of the period. The crossopterygians are now represented by *Polypterus* of the Nile and *Calamoichthys* of South Africa. The *Osteolepis* (Fig. 223), which was closely in the ancestral line of these modern forms, was abundant in the earlier Devonian. Like the lung-fishes, the crossopterygians appear to have been at or near the climax of their evolution in the Devonian period, though the group continued in considerable strength to the Cretaceous.

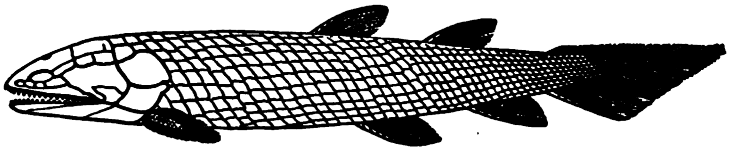


Fig. 223.—Restoration of *Osteolepis* by Pander; about one-fourth natural size; from Old Red Sandstone, Scotland. (From Dean and Woodward.)

The actinopterygians are known to have been represented at this time only by the handsome *Cheirolepis* (Fig. 224), the most primitive of the group, and remarkable among the fishes of the time for the very small size of its scales. It has been found in Scotland and in the Province of Quebec.

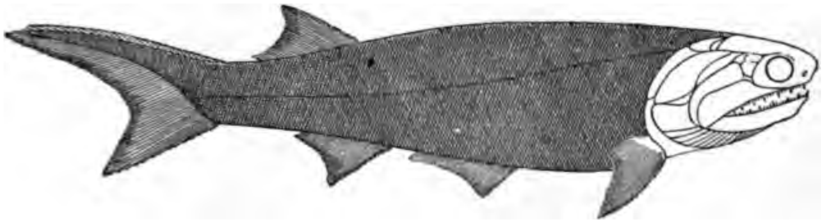
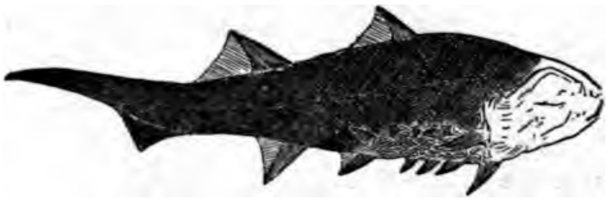


Fig. 224.—Restoration of *Cheirolepis trailli* from Old Red Sandstone, N. Scotland. About one-fifth natural size. (After Traquair and Smith-Woodward.)

The *sharks* (elasmobranchs) are now, and (unless the Paleozoic era be excepted) have been throughout known geological time, chiefly denizens of the sea; but they still occasionally live in fresh water, as in Lake Nicaragua and Lake Baikal. It seems clear that in the Devonian period they lived in the open sea, as heretofore noted, but their remains are also found in the Old Red Sandstone and in the equivalent deposits, and hence it is probable that they lived in fresh and brackish waters also. Prominent among them were the acan-

ıdians, sharks amply armed with fin-spines (such as *Climatius* (Fi
ı) *Diplacanthus, Cheiracanthus,* etc.). There does not appear to l
r clear evidence that the pavement-toothed sharks occupied tl
sh waters, and this is not strange since these probably did not offı
ıugh shell-fish to be inviting feeding-grounds.

The associated arthropods. — In view of the arthropodan relı
ıs of the ostracoderms, it is suggestive that now again, as in tl



ıG. 225.—*Climatius scutiger*, natural size, from Old Red Sandstone, Scotland. (From Zittel, after Powrie.)

ına and in the transition beds of the European Silurian, there wer
ıntic eurypterids associated intimately with the ostracoderms an
fishes. Taken together, these constitute a most remarkable faunı
ı *Pterygotus* now reached the extraordinary length of two meter
ıre were also ostracodes, phyllocarids, and phyllopods related to tl
heria of modern brackish waters. On the land, too, were scorpion
bably related ancestrally to the eurypterids, as well as the
distant kin, the spiders, together with myriapods and insect
bably also ancestrally related to some of the aquatic crustacean
ıas already (p. 482) been suggested that this association of arthr
s and vertebrates ran back to their origin, and it may here
ed that it ran on until the present day, for the fish and the arthr
s (crayfish and smaller crustaceans) dominate the fresh wate
le the terrestrial vertebrates and the insecteans are only too in
e associates and contestants on the land.

Fresh-water mollusks.—Shells believed to have belonged to fres
er mollusks, and closely resembling living genera, have been fou
England, Ireland, Russia, and the United States, accompanied
l plants and by fishes. Some traces of what are supposed to ha
n fresh-water plants have been found, but as yet little is knoı
he aquatic vegetation.

III. THE LAND LIFE.

It is not possible to follow the evolution of the land life with even such partial continuity as has been attempted with the marine life, for the record is much more imperfect and its interpretation more uncertain. The known life consisted of land plants, a few snails, insects, myriapods and scorpions, and mere traces of amphibians.

The land plants.—The dominant element, and the basal one as well, was the vegetation; but there are good reasons to think that its preservation was relatively the poorest. In the early stages of its evolution, vegetation was doubtless more perishable than later, from having acquired less mineral stiffening and less protective investiture of bark, husks, nut-shells, and other less perishable parts; but even in their best estate, plant tissues are less well fitted for fossilization than the shells and skeletons of animals. To this, very adverse terrestrial conditions are added. The normal fate of upland plants is to perish where they grow, and their fossilization is usually prohibited by the constant denudation of the surface. If any part of an upland plant escapes its normal fate, it undergoes usually various contingencies of decay, consumption, combustion, and other forms of destruction, before it reaches a place of sedimentation. If, escaping these, it reaches a lake or the sea, its lightness tends to keep it afloat and render it peculiarly susceptible to shore action and to different forms of organic attack. If it survives these, it is liable to be buried near the shore where subsequent denudation is most likely to cut it away, for the extreme borders of nearly all strata, except in cases of unconformable overlap, are denuded.

In the case of lowland vegetation the chances of prompt burial and preservation are much better, but even here the contingencies of subsequent denudation are large. It is only when the area of sedimentation is creeping out upon the land with relatively little shore cutting, or the low lands are undergoing permanent aggradation, that the conditions for the fossilization of land vegetation are even fairly favorable. Even when preserved, the parts of a plant are apt to be dissevered, and their re-assemblage and interpretation is difficult. It is rare that leaves, fruit, twigs, limbs, trunk, and roots are all retained together. In the case of ancient forms, especially where not closely analogous to modern types, it is more or less hazardous to attempt estore the original plant by combining the dissevered parts of rent individuals. Until these are found associated, it is usually ssary to describe and name the parts separately, and hence the ibility that different species and even genera will be founded on separated parts of the same plant, a possibility that has been zed not infrequently. As discovery proceeds, these are detected the nomenclature revised.

Though occasional relics of land plants have been found in the rian and earlier systems, it was not until the Devonian that land tation was fairly well preserved, but, for the reasons just uced, it is by no means safe to assume that prolific land vege- on had not long clothed the surface, and that, perhaps, of a ewhat advanced order. Physical reasons for assuming a vegetal ection of the surface as far back as Proterozoic times have ady been presented. The study of the Devonian and Carboni- us plants shows that they were widely differentiated, so much so their ancestral relations are uncertain, which is best explained a long previous history. The alternative is to suppose a very d evolution attended by an equally rapid extinction of the inter- iate forms and of the residual structures that usually linger long nark the course of evolution. This alternative is, however, pre- ed by some authors.

The larger part of the Devonian plants preserved were buried nland basins, sometimes mingled with the fossils of fresh-water nals. Of the upland vegetation little or nothing is known. The and forms may have spread over the uplands in greater or less ree, or a very different and quite unknown vegetation may have ailed there. Comparatively few forms have been found in the ier Devonian formations and the apparent evolution during the od is very marked, but it is doubtful whether this represents much e than improved preservation, for the types do not converge rapidly n traced backwards as though they had originated within the od, nor do they diverge rapidly as traced on to the Carboniferous od. The Devonian types were nearly the same as those of the boniferous, and as the latter are much better represented in the l flora, their special description and illustration may be deferred h advantage until the discussion of that period.

The dominant Devonian forms were *pteridophytes* (ferns and their allies) and the lower *gymnosperms*.[1] The angiospermous flowering plants were not represented, so far as known.

The record of the lower plant groups (on the land) is almost negative. There is no evidence of liverworts or mosses (*Bryophytes*) nor of terrestrial algæ and fungi (*Thallophytes*), except that, interestingly enough, bacteria (both *bacillus* and *micrococcus*) have been reported.[2] The identification of such simple forms in fossilized woody tissue at so ancient a period is remarkable, but the presence of bacteria is altogether probable, for there is good reason to think that the decay of vegetation was then, as now, accelerated by bacterial action. Otherwise the vegetal record should be more perfect.

The pteridophytes were represented in nearly every division. Among the *Filicales* there were true ferns (*Filices*), and apparently also forms intermediate between ferns and cycads (*Cycadofilices*, *Pteridospermæ*). The *Equisetales* were represented by calamarians; the *Sphenophyllales* by the type genus *Sphenophyllum*, while the *Lycopodiales* were present in the form of *Lepidodendron* and possibly *Sigillaria*, reported by some authors but questioned by others. The spermatophytes, on the other hand, seem to have been represented only by their lower division, the gymnosperms, and these perhaps only by *Cordaites*, though conifers and ginkgos have been reported. The identifications are, however, questioned.

The general aspect of the ferns was already like that of the existing forms, but the other families were archaic and peculiar. It is not a little singular that forms seemingly so delicate as the ferns should have been among the most persistent and least modified of terrestrial plants. Notwithstanding their relatively modern aspect, they were archaic in many features, and embraced a much wider range of characters than at present.[3] The larger number were herbaceous, but tree-ferns (*Psaronius*), not unlike those now living in the tropics, were present. The ferns were already so far advanced in evolution that little has yet been learned from them relative to their ancestral relations. They are thought to have been the progenitors of the *Cycadofilices* (*Pteridospermæ*), and through them of the cycads and of most or all the other nosperms; but on this point there is not as yet complete unanimit pinion. In numbers, the ferns or fern-like forms appear to hav assed all others.

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[1] For classification see Vol. I, p. 653.

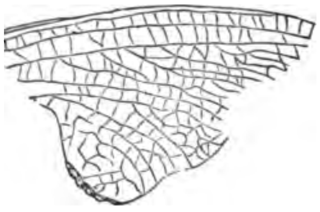
[2] Renault, Ann. Sci. Notes, Vol. II, 1896. See also Steward, Fossil Plants, 1898, pp. 133–138.

[3] D. H. Scott, Studies in Fossil Botany, p. 506.

he forest element was chiefly due to the calamites, gigantic ances- of the horsetails, to the lepidodendrons, gigantic ancestors o club-mosses, and to the cordaites, an extinct group of gymno- mous type. All of these trees were so much better develope e Coal flora, where they reached their climax, that their discussion advantageously be deferred.

here were not a few forms whose relations have not been mad satisfactorily from the imperfect material. Among them ar e known as *psilophyton* and *ptilophyton*.

he insects.—The air was partially peopled by insects at this time. erous wings and other fragments have been found, chiefly nea Johns, New Brunswick, and these have been described and inter- ed by Scudder.[1] The relics indicate that the insects were of archai synthetic types most nearly allied to modern neuropters an opters, but they combined characters now found in different orders representatives of neuropterous aspect seem to have been relate he mayflies (*Ephemera*), whose lives are spent chiefly in water



226.—*Platephemera antiqua*, Sc., Johns, N. B. (After Scudder.)

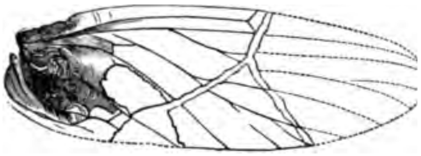


Fig. 227.—*Xenoneura antiquorum*, Sc. Fr St. Johns, N. B. (After Scudder.)

winged condition being assumed for a short period only. If th true of the ancient forms, they should be regarded as aquat er than as aërial denizens, and scarcely as terrestrial at all. B imperfect relics perhaps do not warrant pursuing these consid ns. Fig. 226 shows the wing structure of *Platephemera antiqu* rge species with a spread of wing of perhaps five inches. Th some at least of the Devonian insects were terrestrial vegetable feeders is perhaps indicated by Scudder's identification of a stridulating call-organ attached to the wing of *Xenoneura antiquorum* which implies not only an arboreal habit but an advanced evolution of the hearing organs. Fig. 227 illustrates the wing structure of this species, and shows, imperfectly, the supposed stridulating organ. As cockroaches had appeared in the Silurian, they also were probably present.

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[1] A list is given in Bull. No. 71, U. S. Geol. Surv., 1891. Question has been rais the Devonian age of these.

Other terrestrial forms.—Myriapods, arachnoids, and a scorpion are reported from plant-beds in New Brunswick, referred by Dawson and others to the Devonian. Myriapods were present in England in at least two genera, according to Peach.[1] Terrestrial mollusks are also reported from New Brunswick.

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[1] Proc. Roy. Phys. Soc. Edin., Vol. VII, 1882, p. 179.

CHAPTER IX.

THE MISSISSIPPIAN (EARLY CARBONIFEROUS) PERIOD.

THE time from the close of the Devonian period to the end of th
ozoic era was formerly regarded as a single period. Since th
ations of this period included many important coal-beds, the nam
oniferous was assigned to it. During the course of the Carbon
us period, according to the old definition, the following gener
ence of events seems to have taken place:

(1) Early in the period there was an expansion of the interi
ontinental sea, especially to the westward, decreasing, correspon
y, the area of the land (Fig. 228). The deposits made in the s
ing this stage not only overlap the Devonian beds at many point
rest on strata older than the Devonian. The early Carbonifero
s probably underlie the Great Plains, where the Devonian syste
elieved to be absent, thus pointing to wide-spread submergen
this direction. This interval of sea-transgression constitutes t
major division of the Carboniferous period, as generally defin
has been variously known as the *Subcarboniferous, Lower Carb*
ous, and *Mississippian.* It was brought to a close by wi
ead emergence of the area where sedimentation had been
gress.

(2) During the next division of the period, as the term Carboni
has been used generally, the sea was at first absent from much
area between the Appalachian mountains on the east and
-hundredth meridian on the west. This epoch of emergence see
have been followed by a brief epoch of submergence, and this b
g interval during which the area of the eastern interior maintai
alting attitude, being now slightly above the sea-level and n
htly below it. This period of oscillation constitutes the sec

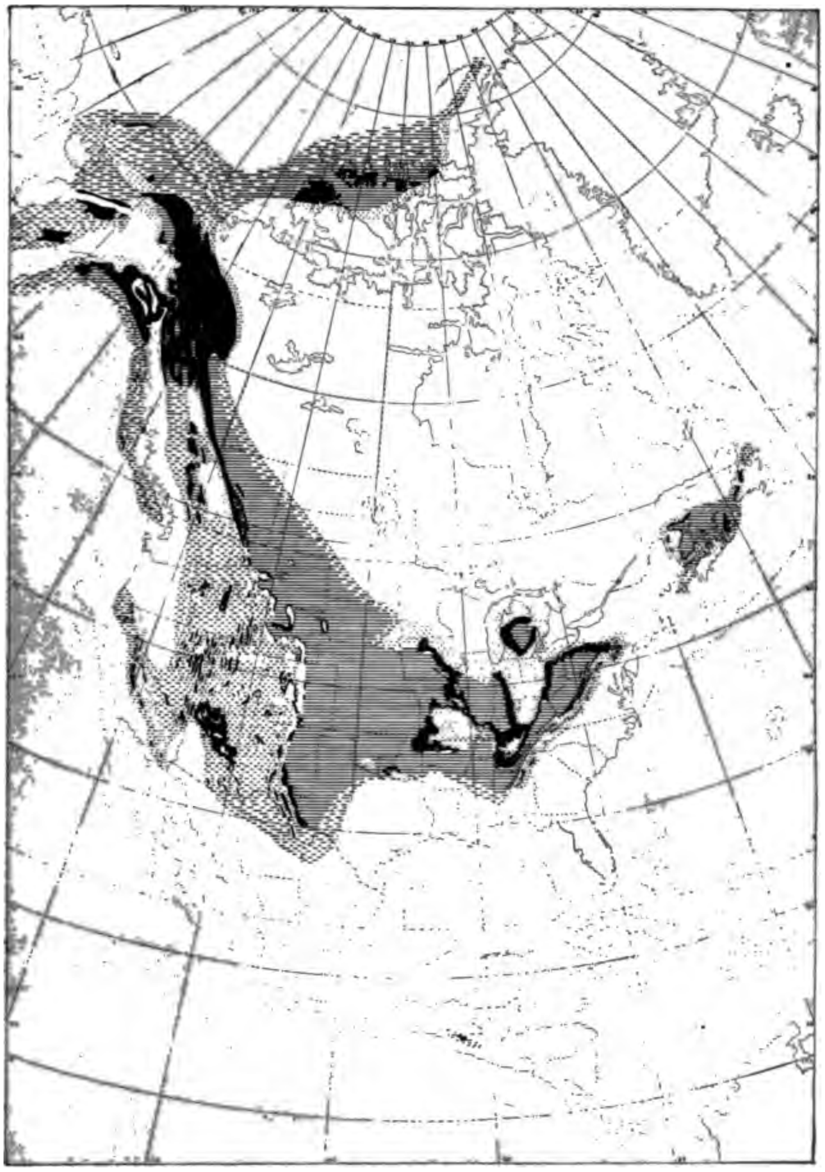


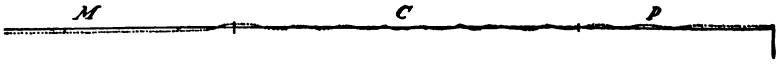
FIG. 228.—Map showing the areas, in black, where the Mississippian system appears at surface. The map also shows where the Mississippian system is thought to exist, though buried (the lined areas), and the areas from which it is thought to have been removed by erosion (the dotted areas). By inference, also, the map shows the relations of land and water during the Mississippian period.

ıt division of the old Carboniferous period, and has been various gnated *Carboniferous, Coal Measures, Upper Carboniferous,* aı *nsylvanian.* West of the Great Plains this second division wa the first, a time of wide-spread submergence.

(3) The third division of the period, as formerly defined, w racterized by a notable deformative movement, which resulte ard the close of the period, in the folding of the Appalachian mou ıs, and less pronounced deformations elsewhere. During the earli t of this movement the record shows merely a general withdrawal sea. Lakes (some of them salt) and partially enclosed seas we eloped at various points where the open sea had been. Near entire top of the true continental platform seems to have emerg he close of the period, and to have suffered more deformation tha occurred at any time since the beginning of the Cambrian perio s division of time is known as the *Permian.*

The general relations of land and water in the middle latitud he eastern part of the continent during the three divisions of tin ıtioned above may be roughly illustrated by Fig. 229.

There has long been doubt as to the propriety of regarding tl mian as a part of the Carboniferous, and though mentioned in th



229.—Diagram illustrating the general attitude of the middle latitudes of astern part of the United States, with reference to sea-level, during the Mississippi ennsylvanian, and Permian periods. The dotted line represents land, the ine, sea level.

nection, it is here regarded as a separate period, coördinate wi Silurian, Devonian, etc.

There seem to be sufficient reasons, also, for regarding the Miss ian or Early Carboniferous formations as a system coördina ı the Silurian, Devonian, etc., and this classification is here adopte reasons for this departure from the current classification will cated after the history of the period has been sketched.

FORMATIONS AND PHYSICAL HISTORY.

The transition from the Devonian period to the Mississippian seems to have been accomplished without notable deformative movement, so far as the larger part of North America is concerned. This is shown by the fact that the earlier formations of the Mississippian period covered most of the area where Devonian sedimentation had been in progress, and that the formations of the later system are, in general, conformable on those of the earlier. These relations hold for both the eastern and western parts of the continent. On the other hand, the Mississippian strata are more wide-spread than the Devonian, indicating that the interior sea of the Mississippian period spread somewhat more widely over the continent than that of the late Devonian period. The Catskill region, except perhaps its western part, appears to have ceased to be an area of sedimentation (compare Figs. 196 and 228), and in the eastern part of the continent, especially in New England and the Acadian region to the north, sedimentation was interrupted, for there the Carboniferous beds often overlie the upturned and eroded Devonian strata unconformably.

The Mississippian period may be looked upon as beginning with the beginning of the continental submergence which followed the Devonian period, and as ending with the emergence of considerable areas of the continent, and a corresponding restriction of the epicontinental sea (Fig. 229). From this definition of the period, it follows that the earlier beds, deposited while the advance of the sea was in progress, are more restricted in their distribution than those of a somewhat later stage, when the continent was more generally submerged beneath the epicontinental sea.

Throughout the period, the interior sea seems to have been bounded on the north, the east, and the south by land, though there were probably connections with the ocean in these directions. To the west it opened broadly, though less is known concerning its extension in that direction. In the interior sea of the east, and in the more open sea of the west, there were the conditions for varied sedi-

Subdivisions.

The following subdivisions of the Mississippian system are recog d in the regions indicated:

issisippi River States.[1]	Ohio.[2]	Pennsylvania.[3]	Maryland.[4]
askaskia or Chester . Louis sage or Augusta (including the Burlington, Keokuk, and Warsaw) inderhook or Chouteau	7. Maxville 6. Logan 5. Black Hand 4. Cuyahoga 3. Sunbury 2. Berea grit 1. Bedford	2. Mauch Chunk 1. Pocono	3. Mauch Chunk 2. Greenbrier[5] 1. Pocono

East of the Great Plains.

n the early part of the Mississippian period, when the sea wa ewhat more expanded than is shown in Fig. 196 and less wide-sprea ı is represented in Fig. 228, the eastern edge of the sea seems t been bordered by high land, for along the western border c alachia coarse sediments (sands and gravels, now Pocono sanc e and conglomerate) were gathering. The land to the north an h of the interior sea seems to have yielded finer sediments. I area east of the Cincinnati arch, the sediments which now coı ıte the lower part of the Waverly series[6] were being deposite h of this sediment may have come from the arch itself, whic have been at first a peninsula and later an island. The are outhern Michigan[7] was a sort of bay or enclosed sea into whic ment was washed from the surrounding lands at the time tl r part of the Waverly series was being deposited east of the Ci ati arch. The association of salt (brine) with the Michigan be

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Williams, Bull. 80, U. S. Geol. Surv., p. 169. *St. Genevieve* was the term appli illiams to the upper part of the Mississippi system.

Prosser, Jour. of Geol., Vol. IX, p. 215, and Vol. XI, p. 520. See also Aı , Vol. XXXIV, p. 335.

Pennsylvania Repts. and folios of U. S. Geol. Surv.

O'Hara, Maryland Geol. Surv., Allegany Co., pp. 109–13.

The Greenbrier is absent in eastern Pennsylvania. It comes in as a lentil tone farther west, and thickens southward, becoming an important formatic irginia, largely replacing the Mauch Chunk shale. See Brownsville-Connell folio, U. S. Geol. Surv. (Campbell.)

Geol. Surv. of Ohio, Vol. VII, pp. 503–815.

ol. Surv. of Michigan, Vol. V and Vol. VII, Pt. II, Huron County.

(Richmondville [Berea] sandstone) is significant of the climate as well as of the geography of the time.

The Kinderhook series.—West of the Cincinnati arch, the conditions of sedimentation were varied as shown by the nature of the formations. In the early stages of the period the sediments laid down were sometimes clastic and sometimes calcareous. The lowest series in the states bordering the Mississippi is commonly known as the *Kinderhook* series,[1] and is characterized by considerable variations in the character of the rock. The sedimentation seems to have varied not only in different places at the same time, but in the same place at different times. The Kinderhook series is to be looked on as representing the time when the sea was in the early stage of its advance.

The Osage or Augusta series.—A little later the waters of the Mississippi River region became clearer, and the varied sedimentation just referred to gave place to the deposition of the more nearly pure limestone. This limestone represents the second or Osage stage of the period. The sea in which this limestone was deposited extended far to the westward, probably to New Mexico on the one hand and to Montana on the other, though between the 97th meridian and the Rockies the strata then deposited are generally buried by later formations. The likeness of the fossils of the Osage limestone of the Mississippi basin to those of the corresponding formation of Europe are thought to indicate some available route of travel for marine species (especially crinoids) between these widely separated regions. What is now known of the distribution of the strata of this stage seems to point to the conclusion that this route was a northerly one, via Grinnell Land and Spitzbergen, or possibly via Alaska and Siberia (Fig. 228). Shallow water and the absence of great variations of temperature are probably the only conditions necessary for such migration as the faunas of these widely separated regions imply. The Osage series of the immediate Mississippi basin, known in Iowa and Missouri as the Augusta series, consists of several subdivisions which have local names.[2] Locally, geodes abound in the series.

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[1] For details concerning the Kinderhook of Missouri, see Weller, Jour. Geol., Vol. IX, pp. 130–48; and Keyes, Vol. VIII, pp. 313–21; and Bull. Geol. Soc. Am., Vol. XIII, pp. 267–92; for Iowa, see Calvin and Keyes, Vols. III and XIII, Iowa Geol. Surv.

[2] See reports of Missouri, Iowa, Illinois, Indiana, etc.

he rich deposits of zinc and lead ore in southwestern Missouri and rn Kansas are chiefly in the Osage (Burlington) beds,[1] though the llic materials were concentrated into ores at a much later time.

uring the second or Osage stage of the Mississippi basin the conns of sedimentation in Michigan seem to have remained much as e Kinderhook stage, and the accumulation of clastic sediments nued.

ast of the Cincinnati arch, which probably remained above water n island, the deposition of clastic sediments was also continued, sediments of eastern Ohio constituting a part of the Waverly s.[2] Still farther east, the accumulation of the sand and gravel e first stage (Pocono) either continued, or had been succeeded he deposition of the mud which now constitutes the Mauch Chunk s.[3] The exact time-relation of these shales to the Osage epoch determined.

hile the Mauch Chunk shales succeed the Pocono sandstone of rn Pennsylvania, with no intervening formation, there is, in western sylvania, a lentil of limestone in the shales. To the south, this stone thickens at the expense of the shale, and in Maryland [4] and nia constitutes a well-defined formation of limestone (Greenbrier) between the Pocono below and the Mauch Chunk above. The man limestone of more southerly regions [5] is perhaps the equivaf the Greenbrier, or of the Greenbrier and Pocono.

he St. Louis formation.—During the third recognized stage of period, limestone (St. Louis) deposition was continued in the ssippi basin, but the fauna which it contains is so unlike that h had preceded as to show that geographic changes of consequence e marine life of the interior had taken place. The changes seem ave been connected with the removal of a barrier somewhere in west, which allowed the fauna of the Great Basin region, heretoshut off from that of the interior, to migrate eastward, and mingle that of the Mississippi basin. This stage marks the time of mum Mississippian submergence, so far as the western interior is rned (Fig. 228).

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ain, Van Hise, and Adams, 22d Ann. Rept., U. S. Geol. Surv., Pt. III.

n addition to the State Reports of Ohio, see Prosser, Jour. of Geol., Vol. IX, 05–31, and Vol. XI, p. 519.

robably of terrestrial origin. Barrell, G. S. A., Dec., 1906.

rosser, Jour. of Geol., Vol. IX, p. 422.

[5] See Tennessee folios.

The peculiar faunal changes which resulted from the geographic changes referred to are discussed elsewhere (p. 518). Suffice it here to say that the fauna of the St. Louis limestone of the Mississippi River region contains species which seem to have lived in the region which is now the Great Basin, but to have been unable to escape from it, at least to the eastward, until this time. Their escape and migration to the eastward at this time is the reason for believing that the barrier which had heretofore restricted them was broken down.

It was perhaps during this epoch that the Bedford limestone of Indiana, famous as a building stone, was deposited. Much of this limestone is foraminiferal, and was long mistaken for oölite. It is in the beds of this epoch, too, that many of the great limestone caves of Kentucky and southern Indiana occur.

In Michigan conditions seem to have remained much as before for beds containing salt (brine) and gypsum (Michigan series) were still in process of deposition,[1] at least during the earlier part of this epoch.

The strata east of the Cincinnati arch have not been definitely correlated with those of the third stage of the period farther west. The limestone-making conditions of the Mississippi River region may have extended eastward, south of the Cincinnati arch, to eastern Kentucky, Tennessee, and West Virginia. Farther north the sediments of this stage were predominantly clastic, and constitute the upper portion of the Waverly series. Locally, deposits of this time contain both coal and iron ore.[2] In the northern part of the Appalachians the Mauch Chunk shales[3] were in process of deposition, while other names (Pennington, Canaan,[4] etc.) are applied to the contemporaneous deposits farther south in the same mountain system. The Mauch Chunk shales contain some iron ore.

The Kaskaskia (Chester) beds.—The fourth stage of the Mississippian period, according to the classification adopted for the Mississippi basin, seems to have been marked by more restricted waters and more varied sedimentation, for sandstone and shale are sometimes associated with the limestone of this epoch. The deposits of this stage nble in a general way those of the first stage (Kinderhook) of period. Those were made while the sea was advancing on the and deepening; these while it was shoaling and retreating. Both more restricted in their distribution than the beds of the interiate epochs. While sedimentation was general over the centra issippi basin, there were probably changes in the relation of lanc water from time to time.

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[1] Geol. Surv. of Michigan, Vol. VII, Pt. II, pp. 13–15.

[2] Geol. Surv. of Ohio, Vol. III, p. 819.

[3] The name Mauch Chunk is applied as far south as Maryland; see Jour. of Geol. Vol. IX, pp. 422–4.

[4] See Tennessee folios.

n Michigan [1] and Ohio the sediments of this stage (Maxville, uppei of Grand Rapids, see p. 500) were partly calcareous and partl ic. Farther east the accumulating beds (upper part of Maucl ık) were clastic.

n summation it may be said that while the Mississippian bed predominantly clastic east of the Cincinnati arch, they are pre inantly limestone west of it, though limestone is not wantin ıe east, especially in the latitude of West Virginia and Marylanc sandstone and shale in the Mississippi basin, especially in the firs last epochs of the period. At many points the Mississippia ɜm carries great quantities of chert.

'he sections of the Mississippian system on pp. 557–563 give som of its character, its range, and its relations.[2]

'he Mississippian system is represented northeast of the Unite ɜs, where it underlies the Coal Measures of Nova Scotia. In th field of this region [3] the Mississippian formations rest on Can ı and pre-Cambrian terranes. The system consists of a thic .ation (2500 feet) of more or less conglomeratic sandstone belov of shale and limestone above. With the shale and limestone ther local beds of red sandstone and gypsum.

In the Great Plains.

Vithin the area of the Great Plains, the Mississippian system vn in Indian Territory [4] (part of the Caney shale, the aggregat thickness of which is about 1500 feet), in eastern Wyoming[1] (Guernsey and part of the Hartville formation), and in South Dakota[2] (Englewood and Pahasapa limestone). A section for this region is given on p. 554.

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[1] ane, Geol. Surv. of Michigan, Vol. VII, Pt. II, pp. 13–15, and 22d Ann. Rep Geol. Surv., Pt. III.

[2] The Mississippian (Subcarboniferous, Lower Carboniferous) is shown in mar e folios of Alabama, Georgia, Tennessee, Virginia, West Virginia, Kentuck Pennsylvania.

[3] Fletcher, Descriptive Note on the Sydney Coal Field, Cape Breton, N. S., 190

[4] Taff, Atoka, and Colgate folios, U. S. Geol. Surv.

In Indian Territory there was some disturbance at about the close of the Mississippian. The beds warped upward (relatively) at this time suffered erosion, and an extensive chert-conglomerate, the conditions for which were prepared by the interval of erosion, marks the early stage of Carboniferous proper (Pennsylvanian) deposition.

West of the Great Plains.

West of the Great Plains the Lower Carboniferous is so widely distributed as to show that the present mountain region as far west as the 117th meridian was mostly submerged, though there were numerous islands,[3] some of which occupied the position of existing mountain cores. North of the United States, marine conditions prevailed east of the Gold Ranges, and again west of those mountains. In general, submergence seems to have been more wide-spread in the west in this period than in the Pennsylvanian period which follows; but in Wyoming submergence was more general in the later period.[4]

The several stages of the epoch, as defined in the Mississippi basin, have not been separately recognized in the west, and, except for the removal (by sinking or otherwise) of the barriers which bounded the Great Basin on the east, it is not known that geographic changes of importance occurred in that region during the progress of the period. Much of the Mississippian system in the west is limestone, though clastic formations are not wanting.[5] The Mississippian formations

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[1] W. S. T. Smith and Darton, Hartville, Wyo., folio, U. S. Geol. Surv. As classified in this folio, there is an unconformity in the Mississippian, but conformity between it and the Carboniferous proper.

[2] Darton, 21st Ann. Rept., U. S. Geol. Surv., Pt. IV, p. 503.

[3] Emmons, Bull. Geol. Soc. Am., Vol. I, pp. 263–7.

[4] Knight, Bull. 45, Wyo. Exp. Station, 1900.

[5] The Mississippian is not differentiated from the Pennsylvanian on the maps of most of the western folios of the U. S. Geol. Surv., though the two are sometimes differentiated in the text. The Carboniferous (Mississippian and Pennsylvanian) is shown in the following folios of the west: *Colorado*, Anthracite and Crested Butte, Pike's Peak, Ten Mile District and Walsenburg; *Wyoming*, Absaroka, Yellowstone and Hartville; ***Montana***, Fort Benton, Little Belt, Three Forks and Livingston; ***Utah***, Tintic; ***Arizona***, Bisbee; and on most of the California folios.

exposed about many of the mountains of the west, and over con
able areas outside the mountains. The system often rests o
Cambrian[1] or Ordovician,[2] as well as the Devonian, and it some
s overlaps all earlier Paleozoic systems and lies upon the Pro
zoic[3] (Algonkian), and frequently attains a thickness of sever
isand feet.

n Colorado[4] the Mississippian is represented chiefly by limeston
dolomite (the Leadville in central Colorado, the Ouray in th
Juan region, and the Millsap in the Front range), 200 to 800 fe
, and is one of the richest ore horizons of the state. The faun
cate the reference of these beds to the Early Mississippian. Th
beds of this system were probably removed in the post-Mississippi
ion interval.

Mississippian limestone occurs in northeastern Washington[5] ai
he Canadian Rockies, where the series is between 6000 and 70
thick, and includes 5100 feet of limestone.[6] The system is ve
rally exposed in the foot-hills of the Rocky mountains. In ma
s of the west it is unconformable beneath the Upper Carbonifero
Pennsylvanian, and in many places there is an unconformity in t
fferentiated Carboniferous which may prove to divide the t
ems. The system is also extensively developed in Alaska,[7] whe
Carboniferous proper is less wide-spread, so far as present kno
is concerned, and also along the Arctic Ocean farther east (F
. In the last-named region the beds are coal-bearing.[8] The Low
oniferous (Mississippian) has also been recognized on Melvi
nd.

Spring Mountain range of South Nevada, Walcott, cited by Spurr, Bull. 2
Geol. Surv., pp. 166–172; and also at various points in the Black Hills of Sou
ta, Darton, 21st Ann. Rept., U. S. Geol. Surv., Pt. IV.

Snake Range, Nevada, Weeks, cited by Spurr, Bull. 208, U. S. Geol. Surv., p.

Smith and Darton, Hartville, Wyo. folio, U. S. Geol. Surv.

Eldridge, Anthracite-Crested Butte folio, U. S. Geol. Surv.; and Girty, Pr
r No. 16, pp. 162, 163, and 217.

Landes, unpublished evidence.

Dawson, Bull. Geol. Soc. Am., Vol. XII, p. 69. Willis thinks some of the b
lated by Dawson with the Carboniferous are Algonkian; Bull. Geol. Soc. A
XIII, pp. 323–5.

Dawson, op. cit., p. 85.

Dawson, Can. Geol. Surv., 1886, pp. 12R, 46–49R, and Map.

Igneous Activity.

During this period, according to present determinations, there was great igneous activity in the west. West of the Gold ranges in British Columbia, the early Carboniferous is made up largely of igneous rock, with intercalated beds of clastic sediments. The area affected by vulcanism at this time, or soon after, extended from Alaska on the north to California on the south.[1] For this region the volcanic activity subsided before the close of the Pennsylvanian period.

CLOSE OF THE PERIOD.

Geographic changes which contracted the eastern interior sea to very narrow limits (Fig. 240), if they did not completely obliterate it, brought the Mississippian period to a close. Similar changes cannot be affirmed to have affected the western half of the continent to the same extent, but the tendency of recent studies is to show that geographic changes of consequence took place even in this part of the continent at this time. Evidence of this import is found in Montana[2] and farther north,[3] where the Lower Carboniferous is more wide-spread than the Upper, in British Columbia,[4] in Colorado,[5] in Indian Territory,[6] where there was perhaps notable warping, and perhaps in Utah.[7]

In some parts of the west, however, so far as now known, marine conditions prevailed uninterruptedly from the early Mississippian period to the later part of the Pennsylvanian period.

Sections of the Mississippian system,[8] at various points in the United es, are given, along with the associated sections of the Pennsy an (Carboniferous proper), on pp. 557–563.

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[1] Dawson, op. cit., p. 85.

[2] Montana folios, U. S. Geol. Surv.

[3] Dawson, Bull. Geol. Soc. Am., Vol. XII, p. 85.

[4] Dawson, Science, March 15, 1901.

[5] Crested Butte quadrangle of the Anthracite-Crested Butte folio, U. S. Geol. Surv. See also 5 below.

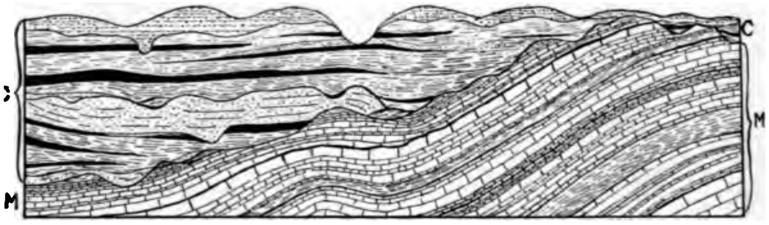
[6] Colgate, I. T. folio, U. S. Geol. Surv., p. 5.

[7] Emmons, Orogenic Movements in the Rocky mountains, Bull. Geol. Soc. Am., Vol. I. Also Mono. XXVII, U. S. Geol. Surv., and Anthracite-Crested Butte folio, U. S. Geol. Surv.

[8] The Mississippian system is not represented as a separate system on the folios of the U. S. Geological Survey; but in the later folios, such as the Indiana, Latrobe, Elkland-Tioga, Masontown-Uniontown, and Brownsville-Connellsville folios of Pennsylvania, the Gaines folio of Pennsylvania-New York, the New Castle folio of Wyoming-South Dakota, and the Edgemont folio of South Dakota-Nebraska, it is represented as a major division of the Carboniferous. In the text of older folios the Mississip-

REASONS FOR REGARDING THE MISSISSIPPIAN A DISTINCT SYSTEM.

[The withdrawal of the sea from a large part of the eastern interi he close of the Mississippian division of the Carboniferous peri osed the newly deposited sediments to erosion. The exposu long and the erosion considerable. At the opening of the Co sures period, as will be seen in the sequel, a large part of this ar



230.—Composite diagrammatic section, showing the unconformity betw Mississippian and Pennsylvanian systems in Iowa. (Keyes, Ia. Geol. Sur

again the site of deposition, and the new system rests unc ably on the Mississippian over wide areas.[1] This is true in pla perhaps generally, in Missouri[2] (Fig. 232), Iowa[3] (Fig. 2 sas,[4] probably in Illinois, in Indiana[5] (Fig. 231), Kentucky[6]

is often clearly separated from the Pennsylvanian, though not as a sepa n.

Missouri Geol. Surv., Vol. VII, p. 422, and Vol. VIII, pp. 340 and 348; I Surv., Vol. IV, p. 282, and Vol. I, pp. 74 and 89; the Univ. Geol. Surv. of K I, pp. 17 and 147; Indiana Dept. of Geol., 20th Ann. Rept., p. 196 et seq., Ann. Rept., p. 101; Charleston, W. Va., Standing Stone, Chattanooga, Lou Wartburg, Tenn.; Richmond and Loudon, Ky., and Gadsden, Ga., folios, U Surv.

Missouri Geol. Surv., Vol. VII, p. 424, and XII, Pt. II, pp. 31 and 209, and Rept., U. S. Geol. Surv., Pt. II, p. 88.

Geol. Surv. of Ia., Vol. V, p. 321, Vol. VII, pp. 79, 210, 426, 503; Vol. IX and Vol. XII, pp. 82, 296, and 448.

Univ. Geol. Surv. of Kans., Vol. I, pp. 16 and 147.

22d Ann. Rept., Dept. of Geol. and Nat. Res., p. 17; and 23d Rept., p. 74, r, Ditney folio, U. S. Geol. Surv.

Loudon and Richmond folios, U. S. Geol. Surv.

Pennsylvania,[1] West Virginia,[2] Maryland,[3] and Tennessee,[4] and the tendency of recent studies is to greatly extend it. (See also sections pp. 557 *et seq.*) In Indian Territory there was disturbance (perhaps orogenic) in the Arbuckle mountains at the close of the Mississippian period.[5]

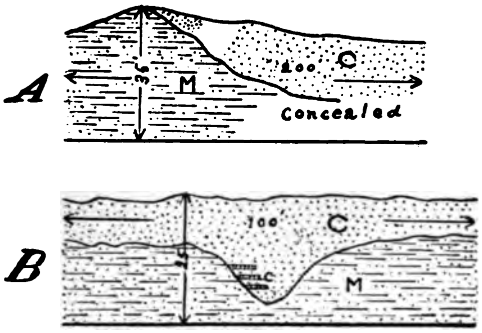


FIG. 231.—Diagrams showing unconformity between the Mississippian and Pennsylvanian systems in Indiana, *A*, at Little Pine Creek; *B*, at Turkey Run (Hopkins: Ind. Geol. Surv.)

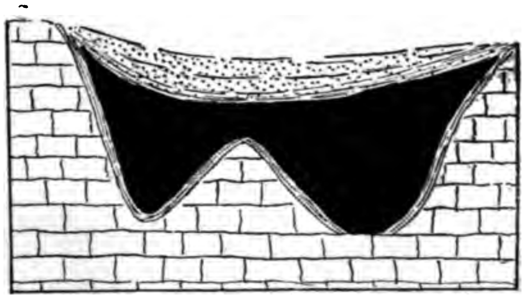


FIG. 232.—Coal in a trough excavated in Mississippian limestone. Cooper Co., Mo. (Winslow, Missouri Geol. Surv.)

This wide-spread emergence, erosion, and submergence, with the accompanying unconformity of the overlying series, is just the sort

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[1] Fuller, Gaines (Pa.-N. Y.) folio, U. S. Geol. Surv.; Campbell, Brownsville-Connellsville (p. 7), Masontown-Uniontown (p. 7), and Elkland-Tioga (p. 3) folios.

[2] West Virginia Geol. Surv., Vol. II, p. 610 (I. C. White); Campbell, Charleston (W. Va.) folio, U. S. Geol. Surv.

[3] White (David), 20th Ann. Rept., U. S. Geol. Surv., Pt. II, and Martin, Md. Geol. Surv., Report on Garrett Co., p. 110.

[4] Maynardville, Tenn., folio, U. S. Geol. Surv. (Keith).

[5] Colgate, I. T., folio, U. S. Geol. Surv. (Taff.)

change which is here held to separate periods (not epochs).
eadly indicated, the geographic changes extended far beyond
tern interior, and even beyond the Mississippi basin. In Colorac
re is a great break in the Carboniferous system which perh
responds to that just noted. Great thicknesses of the Mississipp
tem were probably removed before the deposition of the Penn
ian formations. The relations of the strata below and above
conformity are such as to show not only that great changes of le
t probable orogenic movements supervened. Similar changes
gested by the relations of the earlier and later Carboniferous bed
ah,[2] Montana,[3] and in British Columbia,[4] though their conte
raneity with those of the Mississippi basin has not been establish
en where there is no unconformity between the Lower Carbonifer
l the Coal Measures, as in most of the Appalachian belt, there
notable change in sedimentation, indicating physical changes
nsequence. Nowhere else in the whole course of the Paleozoic
so great physical changes embraced within the limits of one peri
this ground, the Mississippian (or Lower Carboniferous) mi
ll be separated from the Pennsylvanian (Coal Measures) as a se
e system. If the Mississippian and Pennsylvanian are still regar
subdivisions of the Carboniferous period, it should be distinc
lerstood that these epochs, and their corresponding series of f
tions, are much more distinct, physically, than the epochs and ser
earlier Paleozoic periods.

THICKNESS OF THE MISSISSIPPIAN SYSTEM.

In keeping with the variations in the sediments, the thickness
Mississippian system is exceedingly variable. In Pennsylvan
ere the group reaches its maximum development, there is a thi
s of 1400 feet of sandstone (Pocono), with 3000 feet of shale (Mau
unk) above it; but so rapidly do the formations thin to the westwa
t in the western part of the state the equivalent formations ha

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[1] Emmons, Orogenic Movements in the Rocky Mts., Bull. Geol. Soc. Am., Vol
o. XXVII, U. S. Geol. Surv.; Anthracite-Crested Butte; and Ten Mile, Co
s, U. S. Geol. Surv. Also Girty, Professional Paper No. 16, U. S. Geol. Surv.

[2] See 1 above.

[3] Montana folios, U. S. Geol. Surv.

[4] Dawson, Science, March 15, 1901.

a thickness of only 300 to 600 feet. In Maryland the thickness is about 1300 feet.[1] In Ohio the sedimentary beds (Waverly shales) are rather thicker than in the adjacent parts of Pennsylvania. In the region of the Mississippi, where the system is chiefly limestone, it reaches a maximum thickness of about 1500 feet, being thinner to the north and thicker to the south, within the area of its outcrop. Even this great thickness is exceeded in West Virginia, where the limestone is more than 2000 feet thick. In Indian Territory (Sycamore limestone and Caney shale [2]) the Mississippian has a thickness of about 1800 feet, in the Black Hills of South Dakota 275 to 525 feet, in Colorado (Anthracite-Crested Butte region) 400–525 feet, and in the regions of the Grand Canyon of the Colorado in northern Arizona (Red Wall formation) 1800 feet. At any probable rate of accumulation, such great thicknesses of limestone call for very long periods of time. The duration of the period was probably as great as that of some of the preceding Paleozoic periods.

As in preceding periods, the thickest beds of the Mississippian system are in the Appalachian mountains. Here too, where the beds are thickest, they were accumulated in shallow water, suggesting either that subsidence was in progress *pari passu* with the sedimentation, or that inclined deposition took place, as the shallow-water zone crept seaward, *pari passu* with the sedimentation.

The distribution of the uncovered portions of the Mississippian beds in the eastern part of the continent is shown in black in Fig. 228. The beds themselves are of course much more extensive than their outcrops. Within the area of North America they are believed to be concealed by younger beds, largely Pennsylvanian (the lined areas of Fig. 228). They have probably been removed from considerable areas (dotted areas Fig. 228) where they were originally deposited. Like all preceding systems, the Mississippian doubtless has wide distribution beneath the sea, where it is probably thin.

THE LOWER CARBONIFEROUS [3] OF OTHER CONTINENTS.

Europe.—The post-Devonian Paleozoic systems of Europe resemble the corresponding systems of North America in some ways, and are in rast with them in others. The formations in eastern and westei ɔpe, as in eastern and western America, are notably unlike.] ern Europe, two great series, or systems, are included under tl ›oniferous, namely, (1) the Lower Carboniferous, chiefly of marii in, and (2) the Coal Measures or Carboniferous proper, deposit(ly in lagoons, marshes, and lakes, and partly in the sea. The systems correspond, in a general way, to the Mississippian aı ısylvanian, respectively, of eastern North America.

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[1] Prosser, Jour. of Geol., Vol. IX, pp. 422–4.

[2] Taff, Professional Paper 31, U. S. Geol. Surv.

[3] The term Lower Carboniferous is here used, instead of Mississippian, because it is the term in common use in Europe.

˜he relations indicated above do not hold for eastern or for southeı ɔpe. The Upper and Lower Carboniferous formations of southeı ɔpe are like the Mississippian and Pennsylvanian of western Nort ›rica, to the extent that they are chiefly marine. The formatioı astern Europe are not closely analogous to those of any part (th America, the Lower Carboniferous being partly marine aı ly non-marine and coal-bearing, while the Upper Carboniferous ely marine.

ʟike the earlier Paleozoic system, the Lower Carboniferous ope is thicker in the western part of the continent than in tl ern, though the difference is less conspicuous. In Russia, whe t of the preceding Paleozoic systems have had but a fraction thickness which they possess in western Europe, the Lower Ca iferous attains great development.

Though the rocks of the Lower Carboniferous series rest confor on the Old Red Sandstone, or on other phases of the Devoni em, in many parts of Europe, they nevertheless record consid(geographic changes. The early Carboniferous formations ern Europe are of marine origin, while the Old Red Sandsto elieved to have been accumulated in inland basins. Furthermo distribution of the Lower Carboniferous and Devonian is son t unlike, the younger formation occurring at some points wh(older is absent, and *vice versa*. Among other geographic chang ery wide-spread submergence of northern lands in Europe a ι, as well as North America, may be noted.

Fig. 233 represents the general relations of land and water in Eurc ng the period. Fig. 234 shows the same relations in France a immediate surroundings in more detail. In general, the relatic he Lower Carboniferous to the Devonian indicate a somewl ɜ-spread, even if slight, submergence at the opening of the Ea

Carboniferous period. This, it is to be noted, corresponds with the sequence of events in North America.

The Lower Carboniferous system of western Europe, like that of North America, is largely of limestone. So true is this that the period is sometimes known as the period of the Carboniferous limestone. In Great Britain, these formations early received the name of "mountain limestone," and that name has frequently been used in connection with the corresponding formations in North America. The Lower Carboniferous limestone seems to have extended continuously from Ireland and Great Britain over northern France, where it has a thickness of nearly 2500 feet along the base of the Ardennes, through Belgium, and across the present valley of the Rhine into Westphalia. Farther east, it passes into shale, sandstone, and even conglomerate, collectively known as the *Culm*.

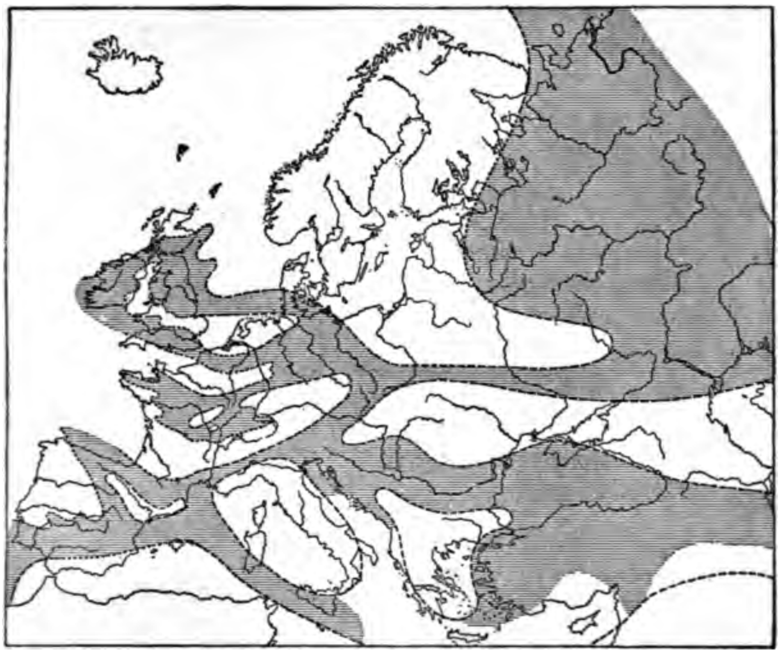
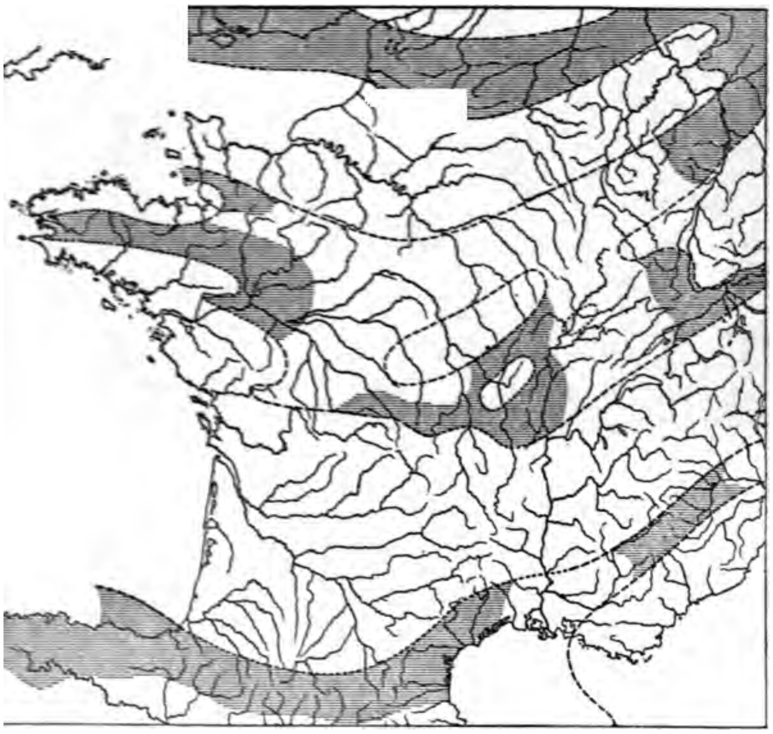


FIG. 233.—Map showing the relations of land and water in Europe in the early Carboniferous period. The shaded parts represent areas of marine deposition. (After De Lapparent.)

Limestone, however, is not the only formation of the Early Carbon-us (Mississippian) period, even in western Europe. Limestone tes clear seas; but the borders of clear seas are often the sites ccumulation of clastic rocks, and the clear waters of the early oniferous sea which extended from Ireland to the north of Europe bordered by shores along which mud, gravel, and sand were deposit- In the north of Britain, for example, near the northern borders ie sea of the period, there are shales and sandstones, and the same



G. 234.—Map showing the relations of land and water in France in the early Carboniferous period. (De Lapparent.)

ue in the south of England along the southern border of the same This facies of the formation corresponds, in a general way, with Culm of the continent, and is sometimes known by the same name. Culm phase of the Carboniferous often contains conglomerates, locally coal.[1] Beds of marine limestone frequently overlie the er Carboniferous coal-seams of Scotland.

[1] Geikie, Text-book of Geology, Vol. II, pp. 1045–1051.

The Lower Carboniferous of Silesia, and of central and southern Russia, differs from that in the western part of the continent, in that it is not all marine, and contains much coal. The coal-field of Moscow covers 13,000 square miles, the system resting conformably on the Old Red Sandstone or its equivalent. The coal-beds are mostly thin and poor. The coal-field of Donetz (southern Russia [1]) covers 11,000 square miles, and contains 44 workable beds (some of them Upper Carboniferous) which have an aggregate thickness of 114 feet. Workable coal-beds also occur in the upturned Lower Carboniferous strata on the flanks of the Urals.

The Lower Carboniferous is wanting in most of central France, and eastward through Bohemia,[2] Moravia, and into the region of the Carpathians. Here the Carboniferous proper (corresponding to the American Pennsylvanian) rests on older Paleozoic systems. This tract was probably land during the Early Carboniferous period. In southern Germany the Lower Carboniferous appears in the mountains only.

The Lower Carboniferous of southern Europe is not very different from that of the central part of the continent, a fact which shows that the northern and southern parts of the continent, which constituted such distinct and persistent provinces during the earlier periods of the Paleozoic, were now less sharply defined.

Lower Carboniferous rocks are also found in Spitzbergen, where they rest on the Old Red phase of the Devonian.

Igneous rock.[3]—The Lower Carboniferous system of Scotland and of central Europe is notable for the large amount of volcanic rock which it contains. Volcanic rocks dating from this period, probably largely from its later part, are found at various points in England, Ireland, and Scotland. In Scotland two great types of eruption are recognized: (1) Plateaus, where the volcanic materials from many vents became continuous over areas hundreds of square miles in extent, the lava sometimes having a depth of 1500 feet; and (2) puys, where the ejections were more local, and centered about the vents which discharged them.[4] As the result of the erosion which has taken place, e volcanic rocks have given rise, in Scotland, to considerable belt .ills and table-lands. Some of these volcanic rocks were probabl ;ubmarine origin, and some of subaërial origin. Igneous rock efly granite) dating from the close of the Early Carboniferou also abundantly associated with the Lower Carboniferous formation he Harz, Thüringerwald, Vosges, and other mountains of centra ope.

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[1] It is not always easy to distinguish the Lower Carboniferous from the Coal Measures of Russia, from the literature which is available.

[2] Kayser, Geologische Formationskunde, p. 196.

[3] Geikie, Text-book of Geology, Vol. II; also Ancient Volcanoes of Great Britain.

[4] Geikie, Text-book of Geology, 4th Ed.

Thickness.—The thickness of the European Lower Carboniferou ery great, considering the fact that it is so largely of limestone. Ir land and Ireland, the limestone attains thicknesses ranging up 000 feet, and perhaps even to 2500 feet. In the northern part of land and in Scotland, where the beds are clastic, they have a thick- which, at the maximum, is much greater. In Belgium, the lime- .e is also very thick. These great thicknesses, especially of lime- .e, bespeak the great duration of the Lower Carboniferous period.) feet of limestone, accumulating at the rate at which limestone is posed to accumulate, would call for at least some hundreds of isands, and perhaps millions, of years. The system also has great kness in Russia.

Close of the Early Carboniferous period in Europe.—The close o Early Carboniferous period was marked, in Europe, by somewha -spread crustal disturbances. It was at this time that a grea em of mountains, sometimes referred to as the Paleozoic Alps, in its development. This system of mountains crossed the centra of Europe, from the islands on the west to the Sudetes mountains erhaps beyond, on the east. Their remnants are seen in the Vosges k Forest, Harz, Sudetes, etc., mountains of the present time. Th elopment of the Ural mountains appears to have begun at the sam . Geographic changes which were not deformative were also i gress, shifting somewhat the areas of sedimentation. In Europ n America, therefore, there is a notable break between the Lowe Upper Carboniferous. Unconformity between the two system ported along the eastern border of the Schiefergebirge[2] in Saxony e eastern Alps, in southern France, and in Spain.[3] These relations

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[1] Kayser, Geologische Formationskunde.

[2] Kayser, op. cit., p. 170.

[3] Credner, Elemente der Geologie, p. 481.

t will be recalled, are in harmony with the phenomena of North America see p. 507), but the unconformity in Europe appears to be less widepread than in North America.

These unconformities are by no means the only indication of georaphic changes at the close of the Lower Carboniferous, for both he distribution of the Carboniferous proper and the character of its ormations point to great changes. The Carboniferous rocks are resent over considerable areas where the Lower Carboniferous appears ever to have been deposited, and they are absent from areas where he earlier system is found. Furthermore, non-marine Upper Caroniferous formations succeed marine Lower Carboniferous, and *vice ersa,* over great areas. The succession first named obtains in western urope, and the second in eastern Europe. Great orogenic moveents began in western Europe at the close of the Lower Carboniferous, nd continued into the Permian.[1] These changes set off the Lower arboniferous from the Upper.

Other Continents.—In other continents, where geological work is ss advanced, the Lower and Upper Carboniferous have not always een carefully separated. The Lower Carboniferous system appears o be somewhat widely distributed in North Africa, and to be present n the southern part of the continent.[2] Lower Carboniferous formations ave been reported in Asia Minor, Persia, in the Kirghiz steppes in entral Asia, in North China and elsewhere. Their faunas are of uropean types, and the system sometimes carries coal.

In Australia (Queensland and Victoria) and New Zealand, the ower Carboniferous consists of marine sedimentary beds which are ften much disturbed and metamorphosed, and associated with more r less igneous rock. In western Australia the Lower Carboniferous ormations (1000 to 1300 feet) contain gypsum and salt.

In South America the Lower Carboniferous is represented in southestern Argentina by sandstone which contains some coal, and in hili. In other parts of the continent it has not generally been sepaated from the Upper Carboniferous.

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[1] Kayser, op. cit., pp. 174–5.

[2] Geikie, Text-book of Geol., Vol. II, 4th ed., p. 1056.

CLIMATE.

Most of the data at hand indicate that the climate of the Lowe oniferous was essentially uniform, and on the whole both genia moist. The fossil plants and corals of so northerly a land as Spitz en, and the relations of the fossils of arctic regions to those o r latitudes, seem clearly to indicate that climatic conditions were ntially uniform in regions where they are now very diverse.

The data which seem to be in discord with the conclusion that climate of the period was genial, moist, and measurably uniform (1) the salt and gypsum deposits of the Mississippian series in tana, Michigan and Nova Scotia, and the similar deposits in ern Australia, all of which suggest aridity, and (2) certain con- erate formations (the Culm) of western Europe.[1] The latter been thought to suggest glaciation, but the evidence does not to warrant this conclusion. The testimony of the marine fos- continues to indicate rather uniform and genial conditions. This ect will be touched on again, in the more general discussion whic ws.

HE LIFE OF THE MISSISSIPPIAN (SUBCARBONIFEROUS).

I. THE MARINE FAUNAS.

Just as there was no profound break in the stratigraphic progres he American continent at the close of the Devonian, so there wa adical break in the succession of life. The Devonian fauna passe gradation into the Mississippian. It will be recalled that the lif ory of the Devonian in North America consisted of a series of grea sions from different quarters, and that the invaders and the invade gled with one another until at the close there was a notable approac single continental fauna. This change, however, was not complet life of the Great Basin was still largely isolated, and there we ndencies of the main fauna that still retained provincial feature During the opening stages of the Mississippian period there wa ontinuation of the movement from provincialism toward cosm politanism. The fauna of the first epoch in the interior basin, the Kinderhook, belongs to the provincial rather than to the cosmopolitan class; for east of the Cincinnati arch there was a rather distinct fauna, the Waverly, and in the Great Basin a fauna that was largely Devonian in type still lingered in measured isolation, taking on slowly a Mississippian aspect. The Kinderhook fauna proper was merely the leading fauna of the interior, occupying the great Mississippian sea, and varying from region to region in response to the different physical conditions already mentioned.

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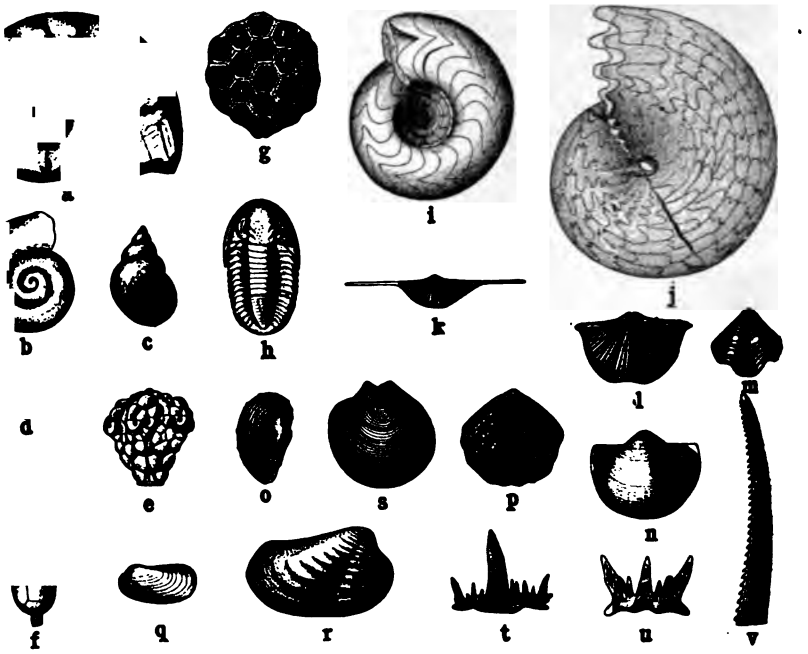
[1] Kalkowsky, Ueber Geroll-Thonschiefer glacialen Ursprungs im Kulm des Franke es. Zeitschr. der deutschen geologischen Gesellschaft, 1893, pp. 69–86.

The Kinderhook Fauna.

One of the more important features of the evolution of the Kinderhook fauna was the progress of the fishes, in which sharks were the leaders; but it will be more satisfactory to treat the fishes of the whole period together after the less roving invertebrate faunas of the several epochs are considered.

The resilience of the crinoideans.—The departure of the Kinderhook fauna from the parent Devonian fauna is shown markedly in the evolution of the crinoids, although, except locally, fossils of these animals are of rare occurrence. They had a very scant development usually throughout the Devonian, and were, in general, quite subordinate to the corals; but in the Mississippian period the relative importance of these groups was reversed. The crinoids not only forged ahead in numbers, but they took on advanced characters. The beginning of this deployment took place in the Kinderhook, and it reached its climax in the next epoch, the Osage, where it will be more fully noticed. Representative forms are shown in Fig. 235, *e* and *f*. Several genera of blastoids were present, all different from those of the Devonian faunas, but they were not as yet abundant, a fact the more notable because of their remarkable development before the close of the Mississippian period. The echinoids and asteroids were still less abundant, a fact in harmony with their very modest development throughout the whole Paleozoic era.

Transition in the aspect of the brachiopods.—The brachiopods of the Kinderhook fauna possess characteristics transitional between those of Devonian and Mississippian types. Among them, the genus *Productus* was conspicuous (Fig. 235, *o*). The Kinderhook species may be said to be anticipatory of the typical Mississippian types,



235.—THE KINDERHOOK (Lower Mississippian) FAUNA. *Gastropoda: a, Por-
llia nodosa* Hall, a shell coiled nearly symmetrically in a plane; *b, Straparollus
tusus* Hall, a low spiral shell; *c, Macrocheilus blairi* (M. and G.), a shell with
moderately elevated spire; *d, Platyostoma broadheadi* S. A. M., one of the capulid
ıells; all four of these genera are present in the Devonian. *Crinoidea: e, Actino-
inus senectus* M. and G., a camerate crinoid belonging to the family *Actinocrinidæ*,
l the members of which are peculiarly Mississippian; *f, Dichocrinus inornatus*
'. and Sp., one of the earliest crinoids with only two basal plates. No such
pe of crinoid base is known anywhere earlier than the Mississippian. With the
evonian, crinoids with four basal plates disappeared, and in the Mississippian,
ıly those with two and three basals are present. *Corals: g, Leptopora placenta*
Vhite), a peculiar compound coral whose relationships are not well understood.
rilobite: h, Pröetus ellipticus M. and W. Trilobites are rare in the Kinderhook
ıd the one here illustrated is a good example of their lack of ornamentation.
ephalopoda: i, Muensteroceras oweni (Hall), one of the abundant species in the
mous Kinderhook goniatite bed at Rockford, Ind.; *j, Prodromites gorbyi* (S. A. M.).
ıis genus has a wide geographic distribution in the Kinderhook, and is the earliest
rm to show secondary lobing of the sutures. *Brachiopoda: k, Spirifer biplicatus*
all, a member of the genus retaining a greatly elongate hinge-line, a character
hich was pronounced among Devonian members of the genus, but not among
ississippian species; *l, Spirifer marionensis* Shum., a species related to such
ecies as *S. disjunctus* of the Devonian (see Fig. 212, p. 476) in its plicated fold
ıd sinus, but it shows an advance in the bifurcating plications upon the sides
the shell; *m, Cyrtina acutirostris* (Shum.), a species of a Devonian genus, no
embers of which persist beyond the lower Mississippian; *n, Productella pyxidata*
all, a representative of a genus which had its great development in the later De-
ɔnian, only a few forms being present in the Mississippian; *o, Productus arcuatus*
all; the genus *Productus* is an outgrowth from the earlier *Productella*, and is
eculiarly characteristic of the Mississippian, Carboniferous, and Permian faunas;
Paraphorhynchus striatocostatus (M. and W.). A striated rhynchonelloid shell
ıaracteristic of the lower Kinderhook horizons of Iowa, northern Missouri and

[*Continued on bottom of p. 521.*]

but at the same time they retained many Devonian features. Not a few Devonian species may be named as the probable direct ancestors of Kinderhook species, as, for example, *Cyrtina hamiltonensis*, as the parent of *C. acutirostris* (Fig. 235, *m*); *Spirifer disjunctus*, of *S. marionensis* (Fig. 235, *l*); *Athyris spiriferoides*, of *A. hannibalensis*. A few species believed to be identical with Devonian forms were also present; indeed the Devonian resemblances (see Fig. 235, *k*) are so strong that the earlier paleontologists referred the Kinderhook to the Devonian, classing it with the Chemung.

Other features.—The molluscan contingent was prominent in the Kinderhook faunas. The pelecypods alone have a larger number of species than either the echinoderms or brachiopods. They are especially abundant in some of the arenaceous beds (Fig. 235, *q*, *r*, and *s*). Among them are species indistinguishable from those of the Waverly fauna that inhabited the gulf east of the Cincinnati island. The gastropods were less abundant, but among them the capulids, a group that was conspicuous among the gastropods of most Devonian epochs were the most common (Fig. 235, *a*, *b*, *c*, and *d*). The chief representatives of the cephalopods were the goniatites (Fig. 235, *i* and *j*), and although they are generally rare, they show, in the genus *Prodromites*, a notable advance over any of their known Devonian ancestors, in the more highly complicated lobing of the suture. Trilobites were few and small (Fig. 235, *h*). Their high stage of ornamentation had passed, the day of their final disappearance was drawing near, and they assumed a sober and subdued aspect. The corals (Fig. 235, *g*), though less abundant than in the preceding epochs, were represented by a considerable number of forms, among which the cup-shaped type was most common.

Though without striking characteristics, the fauna represented a notable stage in the evolution of distinctive Mississippian features. It was essentially indigenous, and may be regarded as a transition stage from the late Devonian to the typical Mississippian fauna represented in the following epochs.

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northern Illinois. *Pelecypoda: q*, *Macrodon missouriensis* (M. and G.); and *r*, *Grammysia hannibalensis* (Shum.), both of which have close Devonian relationships; *s*, *Pernopecten cooperensis* (Shum.), a species very characteristic of certain of the higher horizons in the Kinderhook. *Vertebrata: t*, Tooth of *Cladodus springeri* St. J. and W.; and *u*, Tooth of *Pristicladodus springeri*, St. J. and W., the sharp cutting teeth of sharks; *v*, spine of *Acondylacanthus gracilis* St. J. and W.

The Osage Fauna.

he physical conditions of the Osage epoch present the key t
character of its fauna. Its extended shallow sea, relatively fre
silt, afforded a rich and expansive field for the climacteric evo
n of the varied assemblage of forms that had come together i
preceding epochs under less favorable conditions. There is evi
e also of rather free migratory communication with the Eurasia
inent by one of the northerly routes, since many species, or closel
d species, were common to the faunas of America and Europ
veen an expanding field for home development, and fair facilitie
mmigration and emigration, the conditions were ripe for notabl
ution. In the main it was an indigenous evolution, but the migra
factor gave it a pronounced cosmopolitan aspect.

he climax of the crinoids.—No single group so well characteriz
fauna and expresses its dependence on physical conditions as th
oids, whose abundance and diversity were pronounced (Fig. 23
. The great order of camerate or "box" crinoids (*Camerat*
reached the climax of its career. This was the second clima
e career of these crinoids, and perhaps the greatest. Their cur
own in Fig. 237, in which the curve of the camerate genera is supe
d on the composite genera curve, to show the special evolution
camerates. The rapid decline of the crinoids, almost to extinctio
this climax, as shown by the curve at the right, is one of the mo
rkable incidents in the life history of the invertebrates, an
iew of their interesting and beautiful forms, one to be regrette
in the day of their glory their fecundity was remarkable,
ested by the fact that a single genus (*Batocrinus*) deployed in
than a hundred species (Fig. 236, *d*). Certain genera, especial
ycrinus (Fig. 236, *f* and *g*), *Actinocrinus*, and *Dorycrinus*, we
nguished for their curiously diversified and ornamented form
ornamentation of the crinoids at this time reached some su
rkable degree as was attained by the trilobites just previous
final decadence, and seems to have much the same suggestivene
the relations of climax, ornamentation, and downfall, a relatio
that singularly enough obtains in human history. Wheth
decline and downfall in the two cases were from similar or differe
es we cannot here inquire. The ornamentation of the crinoi

is observable in all of the more prominent families, and seems to be a clear case of parallel evolution. The ornamentation was effected by the development of surface ridgings, nodes, spines, and other outgrowths from the plates.[1] It is even possible to recognize a distinct advance in the ornamentation during the progress of the epoch. In the earlier (Burlington) stage the crinoids were usually smaller and more delicately ornamented than in the later (Keokuk) stage, when they attained larger sizes, assumed broader features, and took on more extravagant ornamentation. The meaning of all this is not clear, but the repetition of this singular phenomenon at different times, and in quite different groups of organisms, is worthy of notice and thought.

The crinoids made large contributions to the limestones, the characteristic deposit of the epoch, the "encrinital limestone" taking its name from the numerous plates and stems which make up much of its substance.

The distant kin of the crinoids were not equally affected by the conditions of the epoch, although the blastoids were represented by a greater variety of forms than at any other period in their history. The starfishes, though present, did not appreciably depart from the slow development that had been their habit for ages, and much the same is to be said of the brittle stars that were even less common. The echinoids showed a slightly greater movement, and left a record of about a score of species.

The scantiness of the corals.—It is a matter of surprise that the corals had so small a place in this fauna, in view of the general physical conditions which were apparently favorable, though there may have been depths or temperatures uncongenial to them (Fig. 236, *u*). Crinoids are less narrowly circumscribed in these respects than corals. It is more likely, however, that the explanation lies in organic conditions, perhaps in the state of the corals themselves, perhaps in unrecorded enemies, parasitic or otherwise, or perhaps in the pre-occupation and rivalry of the crinoids.

Other features.—The brachiopods, as usual, held a leading place

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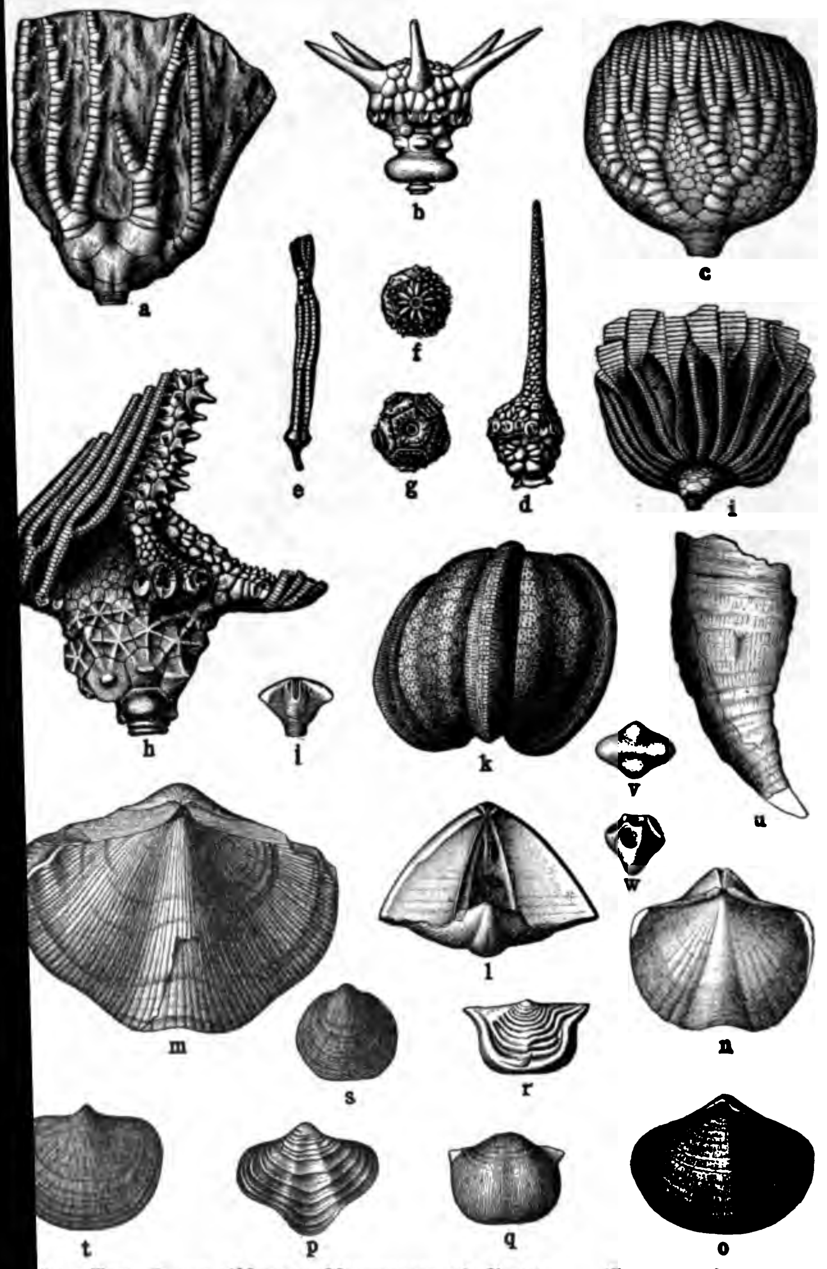
[1] Admirable illustrations may be found in the Monograph of Wachsmuth and Springer on "North American Crinoidea Camerata," Mem. Mus. Comp. Zool., Vols. 20–21, and also in the state reports of Iowa, Illinois, and Ohio, especially Geol. Surv. Ill. Vol. 5.



36.—THE OSAGE (MIDDLE MISSISSIPPIAN) FAUNA. (See opposite page fc
explanation of figure.)

in the fauna, and some of their species had a wide geographic range, extending to the eastern continents. Some of the typical forms are illustrated in Fig. 236, *l–t*. The molluscan factor was subordinate. A few winged pelecypods, a few capulid gastropods, an occasional pteropod, and an even rarer cephalopod, make up the poor representation of this class. The low estate of the cephalopods, so prominent earlier, and to be so again later, is very notable. They were represented chiefly by the *Nautilus* family.

There were a few lingering trilobites and some other crustaceans, a quite ample growth of bryozoans of much interest, some supposed sponges (Fig. 236, *v* and *w*), and doubtless the less easily fossilized

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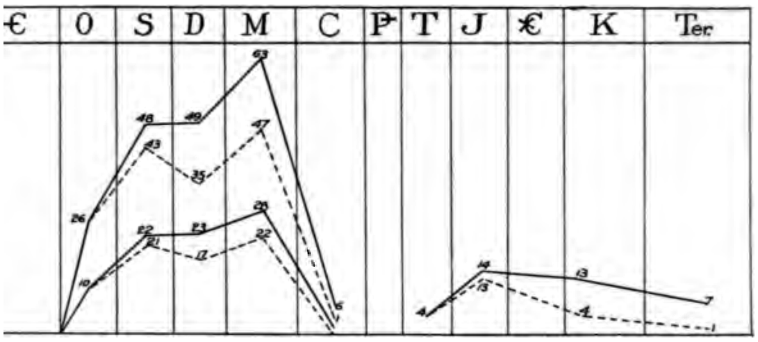
EXPLANATION OF FIG. 236.—*Crinoidea: a, Barycrinus hoveyi* Hall, one of the fistulate, inadunate crinoids, note the persistence of the uniserial arm structure; *b, Dorycrinus missouriensis* (Shum.), a camerate crinoid of the family Batocrinidæ; note the peculiar development of the basal plates and the spinose plates of the vault; *c, Forbesiocrinus wortheni* Hall, one of the flexible crinoids; *d, Lobocrinus longirostris*, (Hall), one of the Batocrinidæ, showing the extravagant development of the anal tube; the arms are removed; *e, Synbathocrinus wortheni* Hall, one of the larviform inadunate crinoids; note the small cup and the simple, uniserial arms; *f, Platycrinus verrucosus* White, and *g, Platycrinus gorbyi* S. A. M.; *Platycrinus* is one of the conspicuous Osage genera; these two figures show different types of ornamentation; *h, Actinocrinus lobatus* Hall; note the high degree of ornamentation of the plates; *i, Eretmocrinus remibrachiatus* (Hall), a representative of a genus of the *Batocrinidæ* characterized by the peculiar spatulate arms. *Blastoidea: j, Orophocrinus stelliformis* (O. and S.), one of the lower Osage blastoids. *Echinoidea: k, Oligoporus mutatus* Keyes. All of the *Palæechinoidea* to which sub-class all Mississippian and Carboniferous sea urchins belong, have more than two rows of plates in each ambulacral and interambulacral area. *Brachiopoda: l, Syringothyris subcuspidatus* (Hall); the genus of which this is a representative is an offshoot from Spirifer, characteristic of the Mississippian faunas; it is characterized by its high area, punctate shell structure, and a peculiar tube between the dental plates; *m, Spirifer logani* Hall, the American representative of the *Spirifer striatus* of the European Mountain Limestone fauna; note the large size, the completely plicated shell, with the plications bifurcating on both the fold and on the sides of the shell. The surface is marked by very fine striæ not shown in the figure; *n, Spirifer suborbicularis* Hall, another type of spirifer, closely allied species of which occur in America and Europe; *o, Reticularia pseudolineata* (Hall), one of the spire-bearing brachiopods having a closely allied species in the European Mountain Limestone fauna; *p, Athyris lamellosa* L'Eveille, a species which occurs both in America and in Europe; *q, Productus burlingtonensis* Hall, one of the species of this peculiarly Mississippian, Carboniferous and Permian genus, which occurs abundantly in the lower Osage; *r, Leptæna rhomboidalis* Wilck, a species which has persisted from Ordovician times, and which appears for the last time in the Osage fauna; *s, Rhipidomella burlingtonensis* (Hall), and *t, Schizophoria swallovi* Hall, two species which are among the last representatives of the orthids, a family whose great development was in the Ordovician; both species have near relatives in the European Mountain Limestone faunas. *Coral: u, Zaphrentis centralis* E. and H., the most characteristic coral of the Osage faunas. *Sponge: v–w, Palæacis obtusum* M. and W. The exact nature of this fossil is not well understood. It is usually placed with the sponges, although by some it is included with the corals. (Weller.)

s necessary to make up a self-sustaining assemblage. Ther



237.—The two upper curves in this diagram, shown in the Paleozoic period ıd their continuation in the Mesozoic, constitute the evolution curve of the enti ass, Crinoidea. The two lower curves in the Paleozoic periods represent tl volution curve of the order Camerata of the class Crinoidea, the order becomi ctinct just before the close of the Paleozoic. The discontinuity of the lines acro ıe Permian column, *P*, represents the imperfection of our knowledge of the Permi unas, and not that the crinoids became extinct in the Pennsylvanian, *C*, to rea ear in the Trias. In all the curves, the dotted line represents the number ew genera initiated, and the full line the total number of genera present, t ifference between the two representing the number of genera which passed ov om the preceding period. The data for the curves have been compiled from t ublications of Wachsmuth and Springer.

beyond doubt an ample marine flora, but it made only a feeb ure record.

The Waverly Fauna.

Contemporaneous with the evolution of life in the successive Kind and Osage seas, there was a rather more provincial developme ıe gulf east of the Cincinnati axis. There was no definite barr veen the gulf and the sea on the west, but, owing partly to t ial separation and more perhaps to the physical conditions, t a in the Waverly gulf was sufficiently distinct to warrant separ gnition.

The Waverly fauna was characterized negatively by the rari oth corals and crinoids, the apparent reason being their depen ce on clear seas. To this there was one notable exception. ıfield, Ohio, there flourished a crinoid field occupied by the spec everal genera. These genera were also represented in the Osa to the west, but the species there were wholly different. Ap ently a colony of their common ancestors had established itself at his locality, perhaps in late Devonian times, and, finding it free from he hostile conditions prevalent in the region, flourished in isolation or a period sufficiently long to differentiate species of its own, after which it died out.

As might be anticipated from the silty conditions, the pelecypods were the most prominent feature of the fauna. Many of them were of the same species as the previous occupants of the region in the closing Devonian times, showing again the close relations of the two periods. The other mollusks were relatively less abundant. Brachiopods were numerous and resembled those of the contemporaneous Kinderhook and Osage faunas; but they were, on the whole, rather less differentiated from the ancestral Devonian forms, doubtless because the change in their environment had been less notable. The other forms were not very different from those of the more open sea to the westward.

The Waverly fauna was the direct descendant of the Devonian faunas that had occupied the same ground and had changed but slowly, as the environment remained nearly constant. It was modified by some immigration of the Kinderhook and Osage types, and this, combined with its own conservative progress, caused it to take on gradually a Mississippian aspect, while it retained many Devonian characteristics. It is a good illustration of a lingering fauna where the conditions are conservative, though not so good an illustration as the next fauna.

The Great Basin Fauna.

It will be recalled that in Devonian times the Great Basin was a province by itself, in which a slow faunal development of provincial aspect, only slightly modified by foreign contributions, took place. At the horizon rather arbitrarily fixed upon as the upper limit of the Devonian system, there appears to have been no faunal break. It is necessary to speak with some reservation, for the region has not yet been thoroughly worked, paleontologically. The transition to the Mississippian facies seems to have taken place very gradually, through the progressive evolution of some forms, the elimination of others, and the immigration of a few from westerly sources, but, until after the Osage epoch, rarely from easterly sources, so far as now known.

distinctive phase of the Great Basin fauna was contemporaneo
the Kinderhook and Osage faunas of the interior sea, and at tl
of the Osage epoch it united with the latter to form the Genevie
Louis-Kaskaskian) fauna.

Previous to this union, one of the most salient distinctions betwe
Great Basin fauna and the Osage fauna was the rarity of crinoi
he former. Although the Osage sea stretched westward to tl
of the ancestral Rocky Mountains, and was prolific in crinoic
do not seem to have invaded the Great Basin sea, one of t
which point to the distinctness of the two provinces. Brachi
were abundant in both provinces, but the species were differe
large spirifers of the type of *Spirifer striatus* (compare Fig. 236, n
haracteristic of the Osage fauna and of the "mountain limeston
urope, as well as other typical forms, were absent. On the ot
l, there had arisen, under the genus *Productus*, probably by p
evolution, species closely allied to some found in the Osage fau
lying that the Great Basin fauna was taking part, in a conser
way, in the Mississippian progress. Were it not for such for
Mississippian aspect, and the evidence that developed when
faunas commingled, the Great Basin fauna might be thou
e Devonian, for there remained many species of marked Devoni
ct. Among these was *Leiorhynchus quadricostatus*, known at
only in Hamilton beds, but in the Great Basin found to commin
he upper horizons with Mississippian types. *Productella*, a De
type, was still living in the Great Basin, although it had dis
ed from the interior after the Kinderhook epoch (Fig. 235,
nerous other species of Devonian aspect were associated with for
lississippian aspect.

Judging from present knowledge, the pelecypods were even m
ndant than the brachiopods, another point of contrast with
ge fauna. The pelecypod species seem to have been peculiar
Great Basin sea, and doubtless originated there, and later beca
nct without migration. There were also many gastropods, am
h were air-breathers (*Physa prisca* and *Zaptychius carbonar*
oldest aquatic pulmonates known. Terrestrial pulmonates, th
ally evolved from aquatic pulmonates, have, however, been
oed from Devonian strata. Cephalopods were not abundant,
oniatites have thus far been found among them. Trilobites w

about as rare as in the eastern fauna, and of the same genera. Corals were present in some abundance, the horn-shaped type predominating. No bryozoans have been reported, nor have any fishes been described. Unless this be due to the imperfection of the record, or of present investigation, it adds much to the evidence of the distinctness of the province, for fish abounded in the eastern sea, and they are free-moving forms of migratory habits.

As remarked in the physical discussion, the barrier which enforced the distinctness of the Great Basin and the Kinderhook-Osage seas appears to have been an elongated insular tract lying about where the Rocky Mountains (not then elevated) now stand. The yielding of this barrier about the close of the Osage epoch, by erosion or submergence, permitted this singular semi-Devonian, semi-Mississippian fauna to invade the greater eastern sea, and, commingling and combating with the Osage fauna, to initiate a new fauna, the Genevieve, the closing fauna of the Mississippian period in the interior. It flourished while the St. Louis and Kaskaskia formations were being deposited.

The Genevieve (St. Louis-Kaskaskia) Fauna.

As remarked in the physical discussion, the St. Louis formation marks the stage of maximum sea-extension in the interior of North America, and the Kaskaskia deposits the inauguration of a restrictive movement. The Genevieve fauna, representing the two stages, may be regarded as the culmination of the cosmopolitan evolution of the Mississippian life on the North American continent, and the initiation of its decline. The commingling of the Great Basin and the Osage faunas was the most declared feature. It introduced into the main Mississippian sea what seemed to be a retrograde feature, although it was a part of the progressive movement toward a more cosmopolitan fauna. Species of a Devonian aspect that had lived along conservatively in the isolated Great Basin province, migrated eastward, and were found among species whose evolution had reached an advanced Mississippian phase. The faunal average seemed to be set backwards. Among these were several productellas, and *Leiorhynchus quadricostatus*, previously mentioned as lingering Devonian forms in the Great Basin fauna. That these really came from the west seems to be confirmed he presence with them, as far east as Arkansas, of *Rhynchonella* *:ensis*, a peculiar and distinctive Nevada species.[1]

'he decline of the crinoids.—Either the invaders, or else changes ıe physical or organic conditions, influenced adversely the crinoids, although they still formed a large factor in the assemblage, they fallen off much from their abundance in the Osage fauna, and undergone notable changes of form (Fig. 238, *a–c*). Less than pecies of camerate crinoids are known in the entire Genevieve a, as compared with upwards of 300 in the Osage. Among these)sage species persisted, and in the faunas younger than those of St. Louis limestone, not even an Osage genus. The inadunate flexible crinoids, however, did not show so remarkable a decline. ɪng the crinoids some new and curious forms were developed, ɪg which may be mentioned *Agassizocrinus* (Fig. 238, *a*), *Ptero- nus* (Fig. 238, *c*), and *Acrocrinus* (Fig. 238, *b*).

:he culmination of the blastoids.—The blastoids had their climax so far as numbers of individuals are concerned, although there much greater generic diversity in the Osage faunas. The leading s, *Pentremites* (Fig. 238, *d*), was so prolific in individuals in some as to give rise to the name Pentremital limestone. A swift decline ıs to have followed this sudden climax, and the beautiful forms ɔpeared for reasons quite unknown.

'he last of the known cystids, a species of the peculiar, horizon- flattened, disk-like *Agelacrinidæ*, a family which had persisted the Ordovician period, was a member of this fauna.

:chinoids were present, among them an ample rotund form sug- vely named *Melonites*, and resembling the *Oligoporus* (Fig. 236, *k*) he Osage epoch. Although the echinoids had appeared much er, it was in the Osage and Genevieve faunas that they for the time showed signs of the prominent development they were to n later.

'artial recovery of the corals.—The corals seem to have profited he decline of their rivals, the crinoids, or by other conditions, for were more numerous than in the Osage fauna. A compound l, growing to great size, *Lithostrotion canadense*, became con- ıous in the St. Louis limestone at some localities. Aside from however, the simple horn-shaped forms remained the most common.

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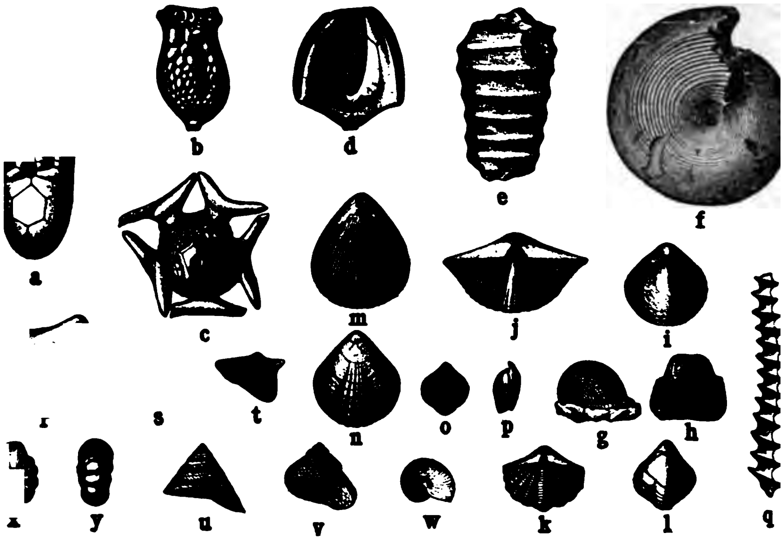
[1] Williams: Am. Jour. Sci., Vol. XLIX, p. 94.

New devices of the bryozoans.—The reticulate bryozoans made a new departure in their mode of support. The delicate branches of their colonies cannot extend themselves indefinitely without special means of support. As one mode of securing this support, the genus *Lyropora* secreted a U-shaped calcareous base, upon the inner concave surface of which the rest of the colony spread itself. As another and more successful mode, the genus *Archimedes* (Fig. 238, *q*), which made its first appearance in the Osage, secreted an axis with a spiral flange upon which the colony spread itself, producing a unique form whose slight resemblance to Archimedes' screw has given it name. The *Archimedes* became so abundant in the Kaskaskia epoch that some beds of the Kaskaskia formations are known as the Archimedes limestone, or account of the great abundance of the axes of this genus.

The protozoans make a record.—For the first time there is clear evidence that the protozoans were an important factor in the fauna. It is not to be understood that they were not really a vital element before, for theoretically there is good reason to believe that they had long been abundant; but they now record themselves in a so-called oōlitic limestone in the St. Louis formation, certain layers of which are almost wholly composed of a foraminiferal shell, *Endothyra baileyi* (Fig. 238, *x* and *y*). On account of their globular form, the shells of this genus have been mistaken for oölitic concretions, and have given a misleading name to the formation.

Changes in the brachiopods.—A notable modification in the aspect of the brachiopods took place (Fig. 238, *g–p*). The large spirifers of the *striatus* type disappeared, though some small spirifers remained (Fig. 238, *j*), while *Productus* (Fig. 238, *g* and *h*) continued to be very abundant and characteristic. *Seminula* (Fig. 238, *l*), *Eumetria* (Fig. 238, *m*), and *Spiriferina* (Fig. 238, *k*) were well represented. An odd feature was the diminutive size of the brachiopods, as well as of all other forms, in the Spergen Hill fauna of the Bedford limestone of Indiana, although they were remarkably abundant. The associated fossils of other kinds were also diminutive, implying general pauperizing conditions of some sort, for the species seem to be identical with those that grew larger elsewhere. It is not improbable that this limestone was deposited in a partially isolated body of water that was so highly charged with lime and other salts as to be somewhat unfavorable to life. A similar diminutive fauna is recorded from Idaho.



238.—THE GENEVIEVE (UPPER MISSISSIPPIAN) FAUNA. *Crinoidea: a, Agassi*
nus dactyliformis Shum., one of the inadunate crinoids which has lost its st
d become a free swimming creature, at least in its adult condition; *b, Ac*
nus amphora, W. and Sp., a peculiarly specialized camerate crinoid with a la
umber of supplementary plates introduced between the basal and radials.
s but two basal plates, not shown in the figure. This genus occurs in the Genevie
d in the Carboniferous, being the only genus of camerate crinoids crossing t
e; *c, Pterotocrinus bifurcatus* Weth. This genus is restricted to the Genevie
unas. It is a camerate crinoid with two basals, and possesses five remarka
ines developed from the ventral surface and produced beyond the arms. *Bl*
dea: d, Pentremites robustus Lyon. Many species of this genus are known
e Genevieve faunas, some species being represented by innumerable individu
phalopoda: e, Orthoceras annulato-costatum M. and W., one of the more anci
aight cephalopods, occasional species of which persisted to the close of t
leozoic; *f, Goniatites kentuckiensis* S. A. M., a notable feature of the Genevie
unas is the recurrence of the goniatites after their absence from the Osage faun
achiopoda: g, Productus marginicinctus Prout, and *h, Productus fascicula*
Ch., two of the numerous species of this genus which constitutes a conspi
s element in the Genevieve fauna; *i, Martinia glabra* M. and W., one of t
achiopods having much closer relatives in the Devonian than in the Osage faun
Spirifer increbescens Hall, one of the most characteristic species of the la
nevieve faunas; *k, Spiriferina spinosa* (N. and P.), a representative of a ge
ich was an outgrowth from Spirifer, and has its greatest development in t
nevieve and Carboniferous faunas. It is characterized by its punctate sh
ucture; *l, Seminula subquadrata* (Hall), a species which has no near ally
e earlier faunas, but is closely related to later Carboniferous species; *m, Eumet*
rcyi (Shum.), a representative of a genus which is abundant in the Genevie
unas and which was also present in the Kinderhook, but absent from the Os
unas until near the close of that epoch; *n, Leiorhynchus quadricostatum* (Va
species common in some portions of the eastern Hamilton faunas, but abs
om the Mississippian sea during later Devonian, Kinderhook, and Osage ti
persisted in the Great Basin region and reappeared in the interior near Bat
le, Arkansas, in a limestone of the age of the St. Louis limestone; *o* and
ynchonella eurekensis Walc., a peculiar Great Basin species which occurs wi
iorhynchus quadricostatum near Batesville, Arkansas. *Bryozoa: q, Archime*

[*Continued on bottom of p. 533.*]

The Mollusks.—The pelecypods (Fig. 238, *r–t*) were rather abundant, ind in some of the sandy and silty beds were the predominant forms. Some of them still retained a Devonian aspect, and those in the Indiana oraminiferal (Bedford) limestone were diminutive, like the brachio-ods of that formation. The gastropods (Fig. 238, *u–w*) were more liversified than in the Osage fauna, and some Devonian genera which ıad apparently been absent from the Osage reappeared. The cephalo-ods (Fig. 238, *e* and *f*) also became more abundant than they had een in the Osage. The goniatites reappear in several species. Pos-ibly these and some of the other mollusks of Devonian aspect which eappeared in the territory from which they had been absent during he Osage epoch came in from the Waverly gulf on the east, and not rom the Great Basin sea from which the Devonian forms previously nentioned quite certainly came. Both of the relatively isolated odies of water appear to have fostered a less rapid evolution than he more open sea between them with its foreign connections and osmopolitan relations. This accords with a general principle in ıistory.

Other forms.—Trilobites were almost unknown, and the other rustaceans left an unimportant record. The sharks and other fish vere important and will be considered presently.

The most striking peculiarity of the fauna, it may be repeated, esulted from the invasion of the more conservative fauna of Devonian ıspect from the Great Basin sea, and perhaps from a similar incursion f lingering forms from the Waverly gulf on the east. The remark-ble thing is that these should have succeeded, so far as they did, n impressing themselves on the composite result, and in giving tone o the whole. It is more natural to expect an antiquated fauna to e overwhelmed by a younger and more progressive one. It would e interesting to know what happened from the counter-migration

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swalloranus (Hall), one of the peculiar screw-like axes for the support of the colony in this genus. *Pelecypoda: r, Schizodus chesterensis* M. and W.; *s, Conocardium prattenanum* Hall; and *t, Conocardium meekanum* Hall, three species of Genevieve pelecypods which have closer relatives in the Kinderhook and Devonian faunas than in the Osage. *Gastropoda: u, Eotrochus concavus* Hall, *v, Pleurotomaria nodulostriata* Hall, and *w, Bellerophon sublaevis* Hall; three gastropods, all from the diminutive Spergen Hill fauna; all of them have nearer relatives in the pre-Osage than in the Osage, and related forms again occur in the Carboniferous. *Protozoa: x* and *y. Endothyra baileyi* Hall, a small foraminifer, much enlarged, which occurs in great numbers in the Bedford limestone of Indiana, it has often been mistaken for oölite grains.

he Osage fauna into the Great Basin region; but this does not
to have been worked out. With little doubt the conservative
ders of the interior sea were favored by physical conditions, which
ar to have grown progressively more and more like those to which
Devonian types had become adapted, and less and less like those
which the special Osage forms were fitted. There is danger, how-
, of over-estimating the Devonian facies, because of its interest.
total assemblage bore a pronouncedly Mississippian aspect.

This persistence of Devonian types through to this, the last recog-
d epoch of the Mississippian period, taken with the close continuity
he life of the last Devonian epoch with that of the first Mississippian
ch, and the absence of any notable physical break at that point,
es the question whether the Mississippian might not better have
regarded as the closing portion of the Devonian period. This
ld have given to the united period a cosmopolitan climax in the
of the Osage-St. Louis limestones, and a fitting close in the decline
any forms, and the unconformity at the summit of the Mississippian.
no divisions of a history, which is in reality continuous, can be
gether without infelicities. The pulsations of the history, which
e are the true basis of natural divisions, are rarely the same every-
re at the same time, and in all their aspects.

With the close of the Mississippian period, the chief center of life
rest passes from the sea to the land, first to the vegetation of the
l period, and then to the land vertebrates. The history of the
ine invertebrates will therefore be followed with less fullness. With
introduction of fishes it had reached its great adjustments, and
further history bears a close likeness to the struggles and adapta-
s of the history already sketched.

The Evolution of the Fishes in the Mississippian Period.[1]

Many of the ancient invertebrates were as fixed as plants, and
r migrations were confined to their early stages; but, quite in con-
t, the fishes were constant rovers, and their distribution was rela-
ly free and rapid. While restrained by conditions of food, tem-
ature, etc., they were relatively independent of local conditions, and

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References: Newberry, Worthen and St. John, Ill. Geol. Surv., Vols. II, IV, VI,
; Newberry, Pal. Ohio, Vols. I and II; Leidy, Trans. Am. Phil. Soc., Vol. XI;
. Woodward, Vert. Pal.; Dean, Fossil Fishes.

the minor stages of their progress are less significant than the general ones. They are therefore discussed here for the period as a whole.

Fish appear to have first effectually invaded the open sea in the Devonian period, but during that period true marine fishes seem to have been inferior, in number and variety, to those of the inland waters. But by the middle of the Mississippian period the marine fishes had made such relative progress that they were in unquestioned supremacy, while the fresh-water forms had notably declined, if we may trust the record. The extension of the epicontinental seas, and the consequent reduction of the land-areas, and doubtless the land-waters, favored the former and restricted the latter. In the seas, the supremacy of the sharks was almost uncontested. The cephalopods, probably the master forms among the invertebrates, were no match for the newcomers and, as already noted, played a very small part in the life of the times. The great sea reptiles and sea mammals, which later preyed upon and kept in subjection the sea fishes, had not yet come to dispute their sway. Under these conditions, and in a new, rich, and expanding realm, it is not surprising that the fish of the period had a really wonderful development. They were apparently much more abundant than in any later period; at least this is true of the sharks. Up to 1889, about 400 species, nearly all elasmobranchs, had been reported from the Mississippian formations of America, and about 200 additional species from Europe.[1]

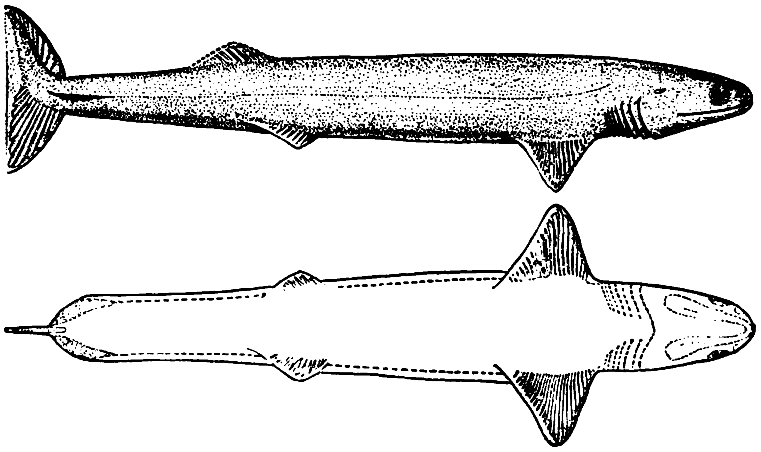
The relics are chiefly teeth, spines, and dermal ossicles, and perhaps the number of species is exaggerated by duplicate naming, though this is doubtless much more than offset by the unrecorded forms. The elasmobranchs held undisputed precedence, and of these at least three-fourths had crushing or pavement teeth, adapted to breaking the shells of mollusks and crustaceans, and the trituration of seaweeds.[2] The tooth-pavement was formed of large plates of thicknesses ranging up to one and one-half inches, composed of solid dentine below and a thick sheet of enamel above, which was pitted, ridged, or otherwise roughened to prevent the slipping of the prey. The multiplication of these chonchivorous sharks introduced a new factor into the invertebrate struggle for existence, and perhaps accounts for the decline or disappearance of some forms and the modification of others.

[1] Newberry, Pal. Fishes, N. Am. Mon. XVI, U. S. Geol. Surv., 1889, pp. 182–83.

[2] Newberry, ibid., p. 184

The number of spines preserved is exceptionally great when com-
ed with the teeth and dermal ossicles, which are about equally
adapted to preservation. The proportion is very much greater
n that of later periods, including the present, and implies that the
ks bristled with spines to a degree not retained in later times.
loss of spines in later ages, like the loss of the armor-plates and
er clumsy defensive devices, may be assigned to replacement by
ity, intelligence, and more effective weapons of attack, as New-
y has suggested; but their great development at this time doubt-
had its special reason in the fact that most of the sharks were
provided with pavement teeth, which were ineffectual weapons
nst those sharks that were armed with piercing and cutting teeth,
hence the former had especial need for a bristling array of spines
defense against their aggressive kin.

Sharks with piercing teeth were represented at the very opening
he period by *Cladoselache*, Fig. 239, and later by *Cladodus* and allied



239.—*Cladoselache fyleri* Newb. Restoration by Dean about one-fifth natural
ize. From Cleveland Shales, Ohio. Often referred to the Devonian. (After
Dean.)

era which were numerous and wide-spread. Some of these were
e and formidable fishes, " armed with teeth in many rows, several
dred in each set." (Fig. 235, *t* and *u*). The petalodonts were a
picuous group of sharks with peculiar cycloid cutting teeth. The
rodirans, which were abundant and gigantic during the transition
od from the Devonian, lingered in reduced importance through

this period and into the next, when they disappeared. The lung-fishes had declined, but were represented by *Ctenodus*. The holoptychians had disappeared, but the crossopterygians were represented by several genera that took on a closer external resemblance to modern forms.

Of the fishes frequenting the inland and coastal waters, probably the culminating type was now actinopterygian of the order to which the modern garpike belongs. The curious tribe of ostracoderms had nearly or quite disappeared.

The fishes probably made up the whole, or nearly the whole, of the vertebrate fauna of the seas. The ostracoderms may have entered the sea, as they are sometimes reported in marine faunas, but they were probably fresh-water forms in the main. There are reasons for thinking that amphibians frequented the fresh waters and the adjacent lands, but probably not the seas.

II. The Land Life of the Mississippian.

Since the period was one of sea extension and its deposits mainly marine, the record of land life is poor. There was doubtless some notable restriction of the terrestrial life by reason of the encroachment of the sea. So far as may be gathered from the record, the main Devonian lines were perpetuated. Enough fossil vegetation has been recovered to show that all the leading groups of Devonian plants were represented. There were true ferns (*Archæopteris*, *Megalopteris*, *Sphenopteris*, *Pseudopecopteris*, etc.) probably *Cycadofilices* (*Alethopteris*), *Equisetales* (*Calamites*, *Annularia*, *Bornia*, *Astrophyllites*, etc.), *Sphenopyllales* (*Sphenophyllum*), *Lycopodiales* (*Lepidodendron*, *Sigillaria*, *Ulodendron*, *Knorria*, *Halonia*, etc.), gymnosperms (*Cordaïtes*), and the fossil seeds *Cardiocarpus*, *Trigonocarpus*, etc., commonly regarded as the fruit of cordaites.

The most interesting suggestion of advance in land life is found in the footprints of a supposed amphibian named *Peleosauropus* (*Sauropus*) *primævus*, described by Lea from the Mauch Chunk shale near Pottsville, Penn. There are six double imprints, in which the track of the hind foot partially covers that of the front foot. They imply a stride of about thirteen inches, and a breadth between outer toes of eight inches. The trail of a tail an inch wide accompanies the footprints. The slab on which they are impressed is ripple-marked pitted by rain-drops, implying a freshly emerged mud-flat aga ered before the impressions were lost.[1] This solitary record prol y stands for many amphibians that had already attained a di tive development, a suggestion that is supported by the rath e differentiation which the amphibians presented when first the e well preserved in the next (Coal Measures) period. The Europe ord is better, nearly complete specimens referred to the labyrinth ts having been found in the Edinburgh (Lower Carboniferou l field of Scotland.[2]

Probably the insects and their allies found in the preceding peri e represented, but their fossils are not known to have been foun

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Dana's Manual, p. 644.

Described by Huxley, under the name *Pholidogaster*, Vol. XVIII, Q. J. G. S.

CHAPTER X.

THE PENNSYLVANIAN (COAL MEASURES, CARBONIFEROUS PROPER) PERIOD.

FORMATIONS AND PHYSICAL HISTORY.

THE system of rocks lying upon the Mississippian was formerly known as the Carboniferous proper, and this name is still in common use. The name has its explanation in the fact that this system contains the great coal deposits of the eastern part of North America. The need of a name to distinguish this system of rocks from those which have been described under the name Mississippian has long been felt, and the name Pennsylvanian, which has recently come into wide use in this country, was adopted because the system is well developed and well known in Pennsylvania. The Pennsylvanian system includes the Pottsville conglomerate (Millstone grit) below and the Coal Measures above.

THE POTTSVILLE CONGLOMERATE (MILLSTONE GRIT).

The lowermost formation of the period in the Appalachian region is generally sandstone or conglomerate (Pottsville conglomerate at the north; Lee conglomerate, Lookout conglomerate, Millstone grit, etc., farther south [see p. 557 *et seq.*]), which betoken shallow water. Over wide areas it is unconformable on the Mississippian system, as already noted. In some places the Pottsville conglomerate appears to be a true basal conglomerate, representing the deposits made by the sea as it transgressed the surface of the recently exposed Mississippian formations. In such places it is sometimes made up partly of the cherts derived from the Mississippian beds, showing that the latter had undergone prolonged decay before the deposition of the conglomerate. In other places the pebbles of which the conglomerate is composed seem not to have been derived from local sources. This like-

argues for wide-spread emergence before the epoch of the Mil
ɜ grit, for on a land surface streams may shift materials grea
ınces.

'rom its coarser conglomerate phases in the east, the Pottsvill
lomerate grades westward into sandstone (Mansfield sandstone
ana,[1] Parma sandstone of Michigan,[2] Graydon sandstone of Mi
i,[3] and Millstone grit[4] of Arkansas), and with local conglomerati
ıes the sandstone persists over the interior. At various points i
east the formation contains thin beds of coal (Fig. 242), showin
local beginnings of the conditions which existed later over wic
s,[5] and in the southern Appalachians it is a chief source of coal
beds of the interior referred to this epoch are thought to repr
the later part of the epoch only, while the series in the Appal
n mountains includes beds referable to earlier stages of the epoc
'ell. In other words, the area of deposition was extended westwa
ıe epoch advanced. Even at the east there is sometimes a great u
ormity between the Mississippian and the Pottsville series (see p. 50
The formation varies in thickness from 1200 feet in the Sou
ıracite basin of Pennsylvania, to as little as 65 feet in some par
vestern Pennsylvania. The unequal thicknesses are due part
he unevenness of the eroded surface on which it rests, partly
ɿual rates of sedimentation, partly to unequal duration of t
of sedimentation in different regions, and partly perhaps to incline
ɔsition, thinning off shore. Half of the formation in easte
ısylvania is thought to have been deposited before depositi
ın in the western part of the state.[7] The formation has a thic
of about 500 feet in Maryland[8] and of 200 to 1500 feet in We
inia.[9] Further details as to thickness are given on pp. 557–66

22d, 26th, and 27th Ann. Repts., Dept. of Geol., etc.

Lane, Geol. Surv. of Mich., especially Vol. VII.

Geol. Surv. of Missouri, Vol. XII, and 22d Ann. Rept., U. S. Geol. Surv., Pt.

Geol. Surv. of Arkansas, Vol. V, 1892.

White (I. C.), West Virginia Geol. Surv., Vol. II.

Hayes, 22d Ann. Rept., U. S. Geol. Surv., Pt. III, p. 235.

White (D.), 20th Ann. Rept., U. S. Geol. Surv., Pt. II, pp. 755–918, and Brow
Connellsville folio, U. S. Geol. Surv., p. 8.

Prosser, Jour. Geol., Vol. IX, p. 422. Also Martin, Maryland Geol. Surv., Repo
arrett Co., pp. 100–110.

White, West Virginia Geol. Surv., Vol. I, p. 211.

The formation is usually so firmly indurated that where it has been tilted its outcropping edge develops ridges.

The Millstone grit, usually a coarse, conglomeratic red sandstone, occurs in Nova Scotia, where it contains occasional lenses of coal and shale.

In the western part of America, the Millstone grit formation has not been recognized. While deposits representing the epoch probably occur, they have not commonly been differentiated from the beds below and above. Locally, however, there are conglomeratic beds which may prove to be the time-equivalent of the Millstone grit of the east. If the Carboniferous (corresponding to Pennsylvanian) of the west is not more generally unconformable on the Lower Carboniferous than present data indicate, the two systems here afford another illustration of the general fact that different regions on the same continent do not always undergo the same changes, or receive similar deposits at the same time. So true is this, that a shallow-water formation, like the Pottsville conglomerate, in the eastern part of the continent, would afford no sufficient warrant for supposing a like formation to have been made in the western. The deposits of the Pennsylvanian (Carboniferous) period in the eastern and western parts of the continent also show that a classification which fits one region may have little applicability to another, so far as details are concerned.

THE COAL MEASURES.

Above the Pottsville conglomerate and its equivalents in the central and eastern parts of the continent lie the formations known collectively as the Coal Measures, a series of beds somewhat unlike any heretofore considered. They consist of a great succession of alternating beds of shale, sandstone, conglomerate, limestone, coal, and iron ore. While the succession differs greatly in different regions, shale and sandstone perhaps recur more frequently than any other members of the series, and in thicker beds. Limestone has a more limited development, and conglomerate is relatively unimportant. The coal and some of the iron ore are in layers interstratified with the clastic beds, and are to be looked upon as strata of rock, the same as the associated sandstones and shale. Important as the coal and iron ore are from an economic point of view, they make up but a small part of ystem. Although there are many beds of coal in some region ılthough some of them have great thickness (40 to 50 feet) tl ırtion of coal in the Coal Measures is rarely one foot in fort; :he proportion of iron ore is much less.

ıe Coal Measures are differently divided in different region ofold division, namely a Lower and an Upper, is common. T series, local names are often applied. In Iowa, for exampl ˌower division is designated *Des Moines*, and the Upper, *Mi* *ın.*[1] In other regions, as in Ohio, a fourfold division h made as follows: (1) Lower Coal Measures; (2) Lower Barre ıres; (3) Upper Coal Measures, and (4) Upper Barren Measure ıst is now generally referred to the Permian period. More recentl ıllowing classification of the Pennsylvanian and Permian systen e east has been proposed[2] and somewhat generally adopted:

ın......	Dunkard formation (or series)	= Upper Barren Coal Measures
lvanian	4. Monongahela " " "	= Upper Productive Coal Measuı
	3. Conemaugh " " "	= Lower Barren Coal Measures
	2. Allegheny " " "	= Lower Productive Coal Measuı
	1. Pottsville " " "	

Distribution and Outcrops.

ıtween the Appalachians and the Rockies.—The distribution 'ennsylvanian system as now exposed is shown in Fig. 240. Tl areas represent the areas where the system is not covered, ı ed only by drift, etc.; the lined areas represent regions whe ystem is believed to exist, though concealed; the areas markı ıshes represent regions where the presence of the system is mo s doubtful; while the dotted portions give some idea of the are ce the system has been removed by erosion. The system is pro concealed over considerable areas to the south of those repr l on the map, where the surface is occupied by younger formation ts equivalent doubtless extends indefinitely under the sea.

is not to be understood that the system everywhere contai in workable quantity, though within the areas indicated co lely distributed (Fig. 241), occurring as far west as the 96th ı

ılvin, Bain, Beyer, Leonard, Young, and Keyes, Geol. Surv. of Iowa, Vo XI, VIII, VII, III, and I. See also Keyes, Am. Geol., Vol. 23, 1893, pp. 298–31

ɾosser, Am. Jour. Sci., 4th series, Vol. XI, p. 191, 1901.

97th meridian in Indian Territory,[1] and nearly to the 100th meridian in Texas.[2]

The distribution of the Pennsylvanian system in the eastern part of the continent, as it now appears at the surface, is in some ways in sharp contrast with the surface distribution of older systems. The commonest position for the outcrops of the Cambrian, Silurian, Devonian, and Mississippian systems severally is around the outcrops of older systems. But this rule does not seem to be followed in the case of the Pennsylvanian, the outcrops of which appear to exhibit no tendency to a similar concentric distribution. Rather do they seem to cover areas between the outcrops of older formations. Thus in Michigan, the Pennsylvanian strata occupy an area completely surrounded by older formations.

This difference in surface distribution does not betoken any real difference in the distribution of the system. The Ordovician formations come to the surface, among other places, in New York, Ohio, Wisconsin, Missouri, and the Black Hills. Beneath the surface, the beds outcropping in these several localities are believed to be continuous, though concealed by younger formations. It will be remembered that most of the eastern interior, and perhaps most of the west as well, became land at the close of the Ordovician period. Had it never again been submerged, the Ordovician system would not have been covered, and its outcrops would now have appeared at the surface not in zones about the exposed parts of earlier systems, but in broad areas between the outcrops of older formations; that is, these outcrops would have corresponded, in principle, with the surface distribution of the Pennsylvanian, so far as it appears at the surface. After the deposition of the Pennsylvanian system, the surface where it is now exposed was elevated, relatively, and except for the glacial drift, was either never deeply covered by later deposits, or if so covered, the overlying formations have been almost wholly removed.

The matter may be looked at in another way. The several land areas, which served as centers for the distribution of sediments, such as Appalachia, the Adirondacks, northern Wisconsin, etc., became, on the average, larger and larger as time went on; that is, the several land areas grew as the result of uplift, or withdrawal of the sea, in of the fact that they were periodically depressed and degrade o temporarily diminished in area. The result of the fluctuatio d and water appears to have been in the long run to the advanta e land. If the apparent changes of level of the land we due to its rising and sinking, the sum of the risings exceed sum of the sinkings. If, on the other hand, the appare es of level of the land were due to fluctuation of the level of t . the *average* movement of its surface was downward. Befo ennsylvanian period,[1] the Ohio island had made its appearanc onstituted a new sub-center of growth. With these sever areas gradually (on the average) enlarging, it is clear that t uation of the process must ultimately have resulted in the . Barring the Coastal Plain, that time came, so far as easte . America is concerned, with the close of the Pennsylvani l. While therefore the Pennsylvanian system of rocks real s in much the same relation to the Mississippian system th of the preceding systems does to its predecessor, its surface di ion seems to depart from the usual rule.

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[1] Gould, Am. Jour. Sci., Vol. XI, p. 185, 1901; and Taff, 22d Ann. Rept., p. 373, Pt. III.

[2] Taff, idem, p. 402.

me of the separate areas of the system shown in Fig. 240 ha bly been isolated since their deposition. Thus the easte r coal-field (Illinois-Indiana area, Fig. 241) may have be uous with the western interior field (Iowa-Missouri-Arkans the separation having been effected by erosion along t sippi, where the Coal Measures have been removed and t sippian formations below exposed. These two coal-fields a ted by a broad low anticline,[2] the existence of which allow ississippi River to reach the Mississippian series the more readi down-cutting. The Coal Measures of different parts of Pen ia (Fig. 240), where the considerable altitude has favored er ave been isolated, though probably once continuous. The figu some idea of the extent of erosion in post-Carboniferous tim oal Measures of Pennsylvania may once have been continuo hose of the eastern Interior, via Kentucky and Tennessee, thoug uncertain. The Michigan [3] and Rhode Island [4] areas (the latt

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[1] Foerste, Bull. Geol. Soc. Am., Vol. XII, pp. 398–444.

[2] Hayes, 22d Ann. Rept. U. S. Geol. Surv., Pt. III, p. 16.

[3] Lane, ibid., pp. 307–331, and Repts. of the Michigan Geol. Surv.

[4] Shaler, Woodworth, Foerste, Mono. XXXIII, U. S. Geol. Surv.

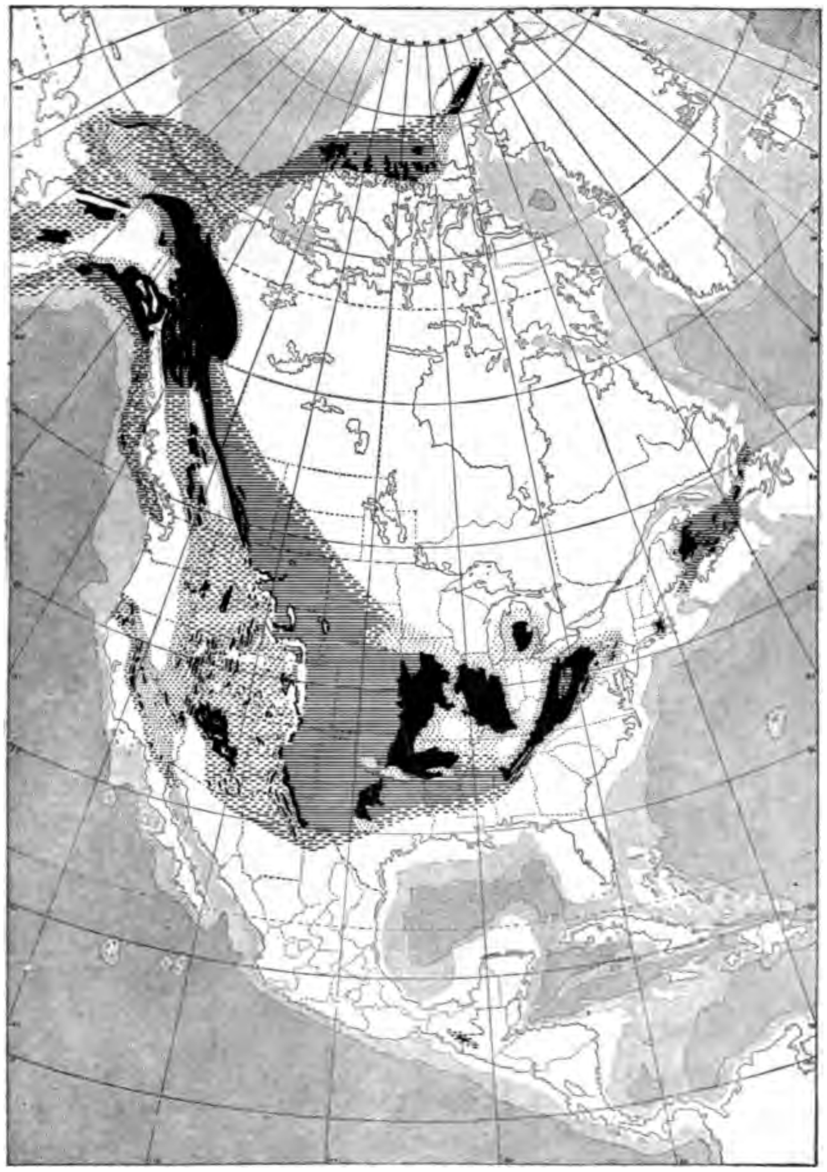

FIG. 240.—Map showing the areas where the Pennsylvanian system appears at the surface in North America. The map also shows, as in preceding similar cases, the areas where the Pennsylvanian system is thought to exist though buried (lined areas); the areas where it is thought once to have existed, but to have been removed by areas (dotted); and by inference the relations of land and sea during the Pennsylvanian period.

shown in Fig. 241) were probably isolated from the beginni
gh at the outset the latter was considerably, and the former son
, larger than now. It is to be understood that, as in the case
ther systems, the present margins of the Coal Measures are r
original margins. At many points, as in Iowa, Tennessee, a
here, there are small outliers of Pennsylvanian formations whi
that the system once extended beyond its present borders.[1]

Productive Coal-fields.

he productive coal areas of the Pennsylvanian (Carbonifero
m in the United States are five in number. These are as follow
1) *The anthracite field,*[3] which is confined to eastern Penns
a, and contains an area of 484 square miles. This aggreg
includes several elongate, nearly parallel, synclinal basins, t
r axes of which have a northeast-southwest direction (Figs.
266). From the adjacent anticlines, and from the neighbori
ower synclines, the coal-bearing beds have been removed
on. The strata of this field may once have been continu
those of the next.

2) *The Appalachian field,*[4] which extends from the northern bor
ennsylvania to central Alabama, a distance of about 850 m
. 240), embraces an area of about 70,800 square miles, of wh
it 75 per cent contains workable coal. Speaking in general ter
western edge of the sharply folded Appalachian belt forms
rn edge of the Appalachian coal-field. Barring a few outly
lines to the east, the strata of this field are gently undulat
orizontal. The formations thicken to the east and thin to
. Few beds of coal are known to have great extent, but the Pi
bed in the Monongahela series, and the Sewanee bed in the Po
series, seem to be continuous over areas of several thousand squ
s.

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or details, see the geological reports of the States where the Carboniferous
s present. Summaries of classifications for Kansas and Nebraska are gi
ser) in Jour. Geol., Vol. VII, pp. 342–56, and Vol. X, pp. 703–17.

Hayes, 22d Ann. Rept., U. S. Geol. Surv. Pt. III, p. 15.

Stoek, idem, pp. 61–117. Also Geol. Surv. Repts. of Pennsylvania.

dem, White (D.), Campbell (M. R.), Hayes, and Haseltine, pp. 127–263.
Geol. Surv. Repts. of Pennsylvania, Ohio, Maryland, West Virginia, Kentuc
ssee, Alabama.

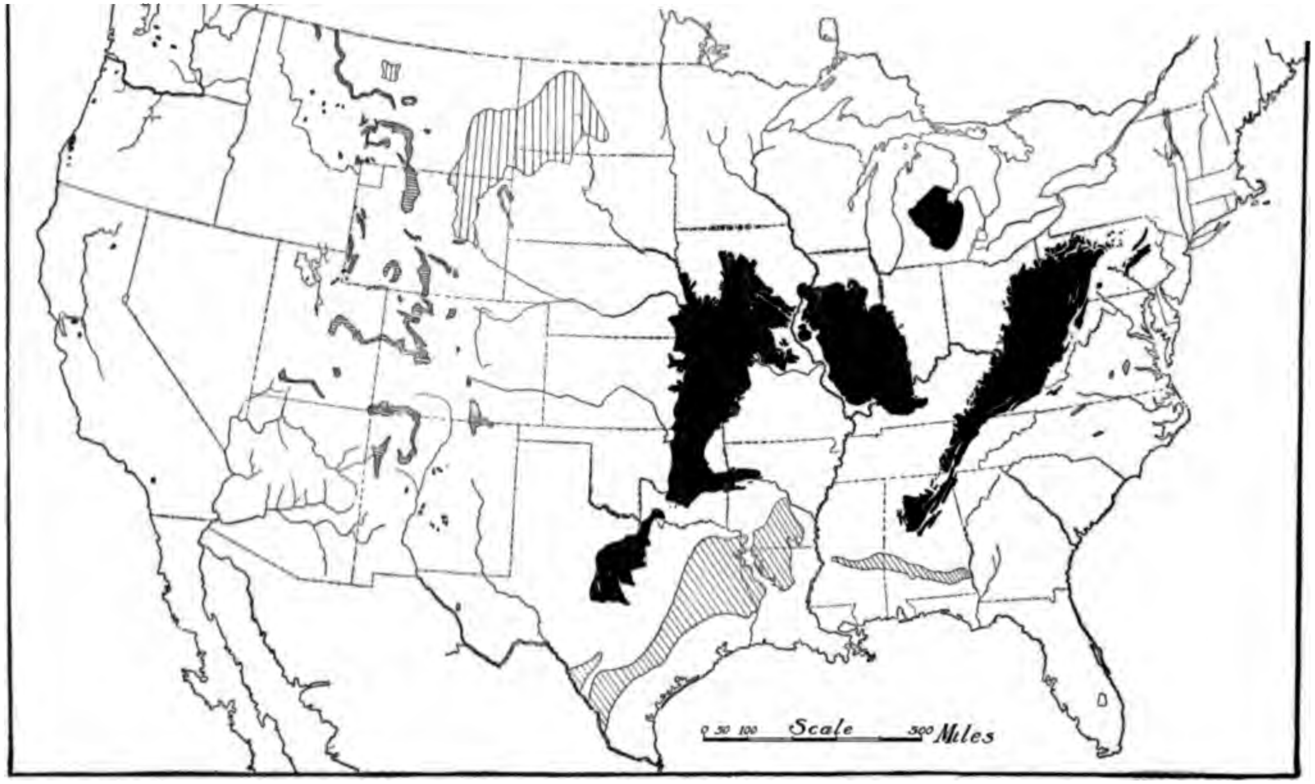

FIG. 241.—Map showing the known distribution of coal in the United States. The black areas are the areas within which coal of the Pennsylvanian system (anthracite and bituminous) occurs. The areas marked by dots in Virginia and North Carolina, represent Triassic (bituminous) coal. Those with vertical (lignite) and horizontal (anthracite, bituminous, and lignitic-bituminous) lines represent coal of the Cretaceous (Laramie) system, and those with diagonal (lignite) and crossed (bituminous and lignitic-bituminous) lines represent coal fields of Tertiary age. The Cretaceous and Tertiary areas include only those where there is known to be workable coal. (U. S. Geol. Surv.)

3) *The Northern Interior field*,[1] which is confined to the southern ısula of Michigan and covers an area of about 11,000 square miles. strata of this field appear to dip gently toward the center of the ı (i.e. toward the center of the Lower Peninsula), but the field heavily covered with glacial drift that its structure is less well vn than that of the other fields. The formations of this basin probably never connected with those of the other coal-fields.

4) *The Eastern Interior field* [2] covers an area of about 58,000 square s in Indiana, Illinois, and Kentucky (Fig. 241). About 55 per of the area is productive. About its borders, the beds of the s are gently inclined, generally toward the center, while in the al part they are nearly horizontal. This field is set off from the ılachian field on the east, and from the Western Interior field he west, by broad low anticlines from which the Coal Measures, er present, have been eroded. The former connection of this field that to the west is probable.

5) *The Western Interior and Southwestern fields* [3] constitute a nearly inuous area of Coal Measures formations, stretching from northern ι to central Texas, a distance of 800 miles, and covering an area 4,000 square miles, including parts of Iowa, Nebraska, Missouri, sas, Arkansas, Indian Territory, and Texas. On the east this is limited by the broad low anticline which borders the Eastern rior field on the west. On the west the field is limited by the lap of younger formations. Except in Arkansas and Indian itory, where the strata are folded, the beds of the Coal Measures iis area are essentially horizontal.

6) *The Nova Scotian-New Brunswick coal-field.*—This lies on both of the Bay of Fundy and contains an area estimated at about)0 square miles. There are numerous beds of coal several of h are workable. The coal is bituminous and of good quality.

Vhile the Pennsylvanian system was perhaps less widespread than Mississippian, in the Mississippi basin, the less extensive system times overlaps the more extensive, as shown on the map (p. 218), where the Pennsylvanian rests on formations older than the Mississippian. This is the case in Illinois,[1] Iowa,[2] Indian Territory,[3] and elsewhere. The absence of Mississippian formations in these several situations may be due either to failure of deposition, or to post-Mississippian-pre-Pennsylvanian erosion.

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[1] Lane, 22d Ann. Rept. U. S. Geol. Surv., Pt. III, pp. 313–331, and Repts. of the Surv. of Michigan.

[2] Ibid., Ashley, pp. 271–305, and Repts. of the Geol. Survs. of Indiana, Illinois, Kentucky.

[3] Ibid., Bain and Taff, pp. 335–413. Also State Geol. Surv. Repts. of Iowa, Missouri, as, Nebraska, Arkansas, and Texas.

Figs. 242 and 243 illustrate further the constitution of the system in the east, and Fig. 244 its structure at a point in the western part of the Appalachian Mountain system.

East of the Appalachians.—The Carboniferous system occurs in the vicinity of Narragansett Bay,[4] where it has an aggregate thickness of about 12,000 feet, and often rests on beds of Cambrian age. The Mississippian system appears to be wanting in this region, thus affording another bit of evidence of the distinctness of the Pennsylvanian and Mississippian periods. The Pennsylvanian system of this region carries coal, which is, however, too highly anthracitic (or graphitic) to burn readily. The beds are much deformed and locally highly metamorphosed. They are associated with igneous rocks, some of which are pre-Carboniferous.

Carboniferous rocks of undetermined extent occur at other points in New England,[5] where they are partly igneous (Fig. 245) or meta-igneous, and partly meta-sedimentary. They are sometimes so completely metamorphic as to make the determination of their age and relations difficult and uncertain.

Northeast of New England, in Cape Breton, Nova Scotia, and New Brunswick, the Pennsylvanian system is extensively developed. Its general constitution, including rich beds of coal, is similar to that of the corresponding system in the eastern part of the United States. From the nature of the formations, the existence of conditions similar to those in the eastern interior is inferred. In Nova Scotia the system attains a thickness of some 13,000 feet.

West of the Great Plains.—Formations made during the period when the Pennsylvanian system was accumulating in the east are

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[1] Reports of the Geol. Surv. of Illinois and geological map of Illinois.

[2] Reports of the Geol. Surv. of Iowa and geological map of Iowa.

[3] Coalgate folio, U. S. Geol. Surv.

[4] Shaler, Woodworth and Foerste, Geology of the Narragansett Basin, Mono. XXXIII, U. S. Geol. Surv.

[5] Emerson and Perry, Geology of Worcester, Mass ; also Perry, Jour. Geol., Vol. XII, p. 7.

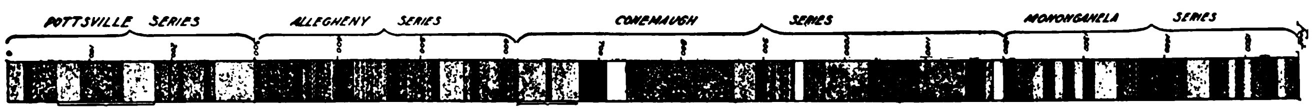

Fig. 242.—Composite section of the Pennsylvanian system of Pa. compiled from various sources. The Pottsville portion of the section is from Mercer Co. (I. C. White); the Allegheny portion from Armstrong Co. (White [David] and Campbell); the Conemaugh portion from Fayette Co. (I. C. White); the Monongahela portion from Fayette Co. The black bands represent coal, the checked pattern limestone, the dots sandstone, and the broken lines shale (Stevenson). (U. S. Geol. Surv.)

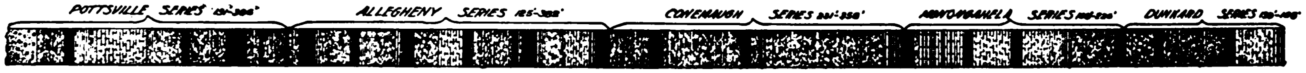

Fig. 243.—Section of the Coal Measures in Ohio. The conventions are as in Fig. 242 (Haseltine, U. S. Geol. Surv.).

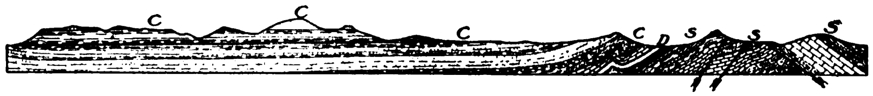

Fig. 244.—Section showing the position and relations of the Carboniferous section near Estillville, Ky. C = Carboniferous (including Mississippian); D = Devonian; S = Silurian. Length of section about 16 miles (Campbell, U. S. Geol. Surv.).

widespread west of the Great Plains, and probably underlie the Plains themselves. With rare exceptions, these western beds, largely of limestone and sandstone, represent the coal-less phase of the Pennsylvanian (Upper Carboniferous) system, a phase which is far more widespread, the whole earth considered, than the coal-bearing phase. There is probably no other continent where the rocks of the period are so generally coal-bearing as in North America; yet even here the coal-less phase of the system is probably more extensive than the coal-bearing. The abundant coal of the west does not belong to this system, but to later ones (Cretaceous and Tertiary). While therefore there are large areas where coal constitutes a part of the Carboniferous system, the formations of this period do not all contain coal, nor are all workable coal deposits referable to this period. In this case, as in others yet to be described, the exceptional and relatively local phase has been taken for the type, partly because it was the part first studied, and partly because it is of great industrial importance.

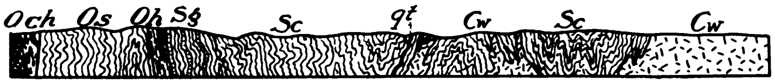

FIG. 245.—Section in southwestern Massachusetts, showing the position and relations of the Carboniferous system. *Cw* = igneous rock, Carboniferous; *Sc* (Conway schist) and *Sg* (Goshen schist) are Silurian formations; *Oh* (Hawley schist), *Os* (Savoy schist) and *Och* (Chester Amphibolite), are probably Ordovician, though classed with the Silurian in the Hawley folio. (Emerson, U. S. Geol. Surv.).

The Mississippian and Pennsylvanian systems have not always been differentiated west of the Great Plains. With rare exceptions, the formations of this system (or of the two systems together) are such as to indicate that marine conditions prevailed in the west. Locally at least (p. 508), sedimentation was interrupted at the close of the Mississippian period, and the tendency of the rapidly increasing knowledge of the west is toward the view that unconformity between the Lower and Upper Carboniferous is somewhat widespread.[1] Furthermore, the formations of the Pennsylvanian period are not in general so widespread as those of the Mississippian, thus affording evidence as significant as that of unconformity of the geographic changes of the time.

From the nature of the formations, it is clear that sedimentation in the western part of the continent was effected under conditions different from those which prevailed farther east. In the region roductive coal, marine conditions seem to have recurred more iently and to have been of longer duration in the western coal- ; than in the eastern. These relations suggest that now and ı the marine conditions of the west extended to the east, as the t of subsidence in that direction, though it does not appear that ea-water at any time became deep within the regions where the occurs. On the other hand, it now appears that the conditions e east sometimes prevailed, at least locally, in the west, for carceous beds, and even beds of coal, are known in the system in Ari-[1] and perhaps in New Mexico.[2] In some parts of the west, the oniferous system includes formations which closely resemble ' Red Beds " of the Permian. This is true, for example, in some ; of Nevada,[3] where the separation of the Pennsylvanian system the Permian is not very distinct, or has not been carefully worked

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[1] See foot-note, p. 510.

'he Carboniferous (Pennsylvanian) system of the west includes rts of sedimentary rocks, among which are considerable thick-s of limestone. They are exposed at many points (Fig. 240) their existence over wide areas where they are now covered b deposits is certain. The Carboniferous of the west is, however, no nuous. Numerous islands of older rock probably maintaine selves throughout the period, and a large area of land existe ghout the Paleozoic era in western Nevada (west of long. 117° had an unknown extension north and south.

n the Carboniferous system of some parts of Colorado (El ntains and Sangre de Cristo range) and New Mexico, there is ble unconformity, with great accumulations of conglomerate,) to 6000 feet thick, at the base of the upper (probably Penn nian) system. Some of the bowlders of the conglomerate ar to be 50 feet in diameter. The unconformity seems not to b ersal, and the conglomerate is, so far as known, rather local. Bot omena have been attributed to notable orogenic movements

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Blake, Am. Geol., Vol. XXVII, 1901, p. 161; also Dumble, Am. Geol., Vol. XXX).

Southwest of Las Vegas, unpublished evidence.

Spurr, Bull. 208, U. S. Geol. Surv., pp. 166–173.

Emmons, Orogenic Movements in the Rocky mountains, Bull. Geol. Soc. Am. I.

and to the great erosion which followed. Beds of finer sediment succeed the conglomerate. On the basis of fossils, the older beds of the Pennsylvanian system in Colorado are thought to be older than the basal beds of the same system in Nebraska and Kansas.[1]

West of the Great Plains the outcrops of the Carboniferous strata often occur about the areas of older rock, where uplift and erosion have exposed them. They appear as narrow borders about various mountain ranges in South Dakota, Montana (mostly Mississippian), Idaho, Wyoming[2] (where submergence was much more extensive in the Pennsylvanian than in the Mississippian period), and Colorado. Some of the fault-block and monoclinal[3] mountains of the west are composed largely of Carboniferous limestone, and here the outcrops cover large areas. The same formations appear at the surface in large areas, in the southwest, especially Arizona, not in immediate association with mountains (Fig. 240). In Nevada, the Carboniferous (Mississippian or Pennsylvanian) formations rest on Cambrian or Ordovician with apparent conformity.[4]

Figs. 246 to 251 show the positions and relations of the Mississippian and Pennsylvanian systems at various points in the west. In most cases the sections are from regions where the strata have been much disturbed by folding, faulting, and the irruption of igneous rock. In all cases the Carboniferous beds are indicated by *C*, or some combination of letters beginning with *C*. Fig. 246 shows the Carboniferous system of the Black Hills, somewhat deformed, resting on the Cambrian, and largely covered by younger formations. Fig. 247 shows the relations of the systems in the Yellowstone Park; Fig. 248 (Colo.) shows the system affected by igneous rock; Fig. 249 (Utah) shows the system where it has been notably affected by intrusions of igneous rock, the latter having, in its ascent, torn off and included masses of the stratified rock; Fig. 250 (Ariz.) represents a section where faulting has produced complicated stratigraphic relations; while 251 (Cal.) shows the system where it is notably deformed and metamorphosed. Figs. 244 and 245 show the system in still other relations.

West of the Paleozoic land area, which, in the vicinity of the 40th

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[1] Girty, Professional Paper, No. 16, pp. 258–267.

[2] Knight, Bull. 45, Wyoming Experiment Station, 1900.

[3] Keyes, Am. Jour. Sci., Vol. XV, 1903, p. 207.

[4] Weeks (cited by Spurr) and Spurr, Bull. 208, U. S. Geol. Surv., pp. 32 and 166–172.

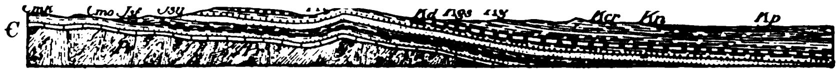

FIG. 246.—Section showing the structure and relations of the Carboniferous in the southern part of the Black Hills region of South Dakota. *Pr* = Proterozoic; *Cmk* (Minnekahta limestone) and *Cmo* (Opeche formation) = Carboniferous; *Jsf* (Spearfish shale) and *Jsu* (Unkpapa sandstone) = Jurassic; *Kd* (Dakota), *Kgs* (Graneros shale), *Kg* (Greenhorn limestone), *Kcr* (Carlile formation), *Kn* (Niobrara formation), and *Kp* (Pierre shale) = Cretaceous. Length of section about 12 miles. (Darton, U. S. Geol. Surv.)

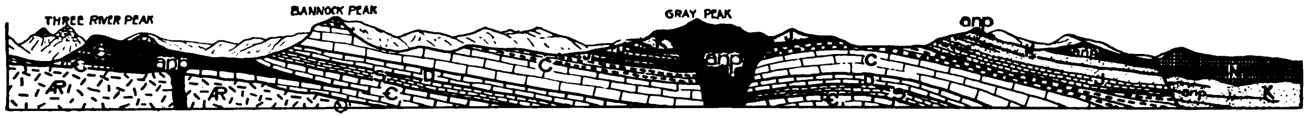

FIG. 247.—Section shows position and relations of the Carboniferous system (as well as others) in the Yellowstone Park. *Æ* = Archean, *Ꞓ* = Cambrian, *S* = Ordovician and Silurian, *D* = Devonian, *C* = Carboniferous, *J* = Jurassic, *K* = Cretaceous, *N* = Neocene, and *anp* = igneous rock. Length of section about 17 miles. (Hague, Iddings, and Weed, U. S. Geol. Surv.)

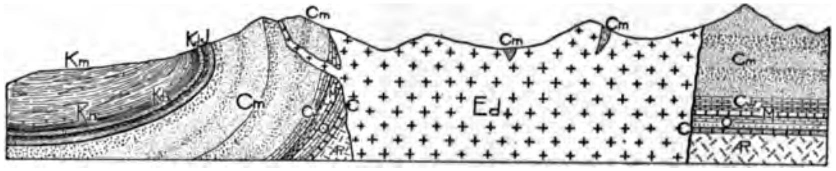

FIG. 248.—Section showing the position and relations of the Carboniferous system at a point in Colorado. *Æ* = Archean; *Ꞓ* = Cambrian (Sawatch quartzite); *O* = Ordovician (Yule limestone); *M* = Mississippian (Leadville limestone); *Cw* (Weber formation) and *Cm* (Maroon conglomerate) = Carboniferous; *J* (Gunnison formation) = Jurassic; *Kd* (Dakota formation), *Kb* (Benton shale), *Kn* (Niobrara limestone), and *Km* (Montana formation) = Cretaceous. Length of section about 6 miles. (Eldredge, U. S. Geol. Surv.)

parallel, lay west of the 117th meridian, Carboniferous strata are known at various points. They make up the body of the Blue mountains in Oregon,[1] they occur in the Klamath mountains of northern California and southern Oregon,[2] at many points in the western portion of the Sierras in California,[3] and probably in the Cascade Mountains of Washington.[4] It is possible that the Carboniferous seas surrounded the great land area which lay between longitude 117° and 121° in the vicinity of the 40th parallel, and which had an unknown extension north and south.

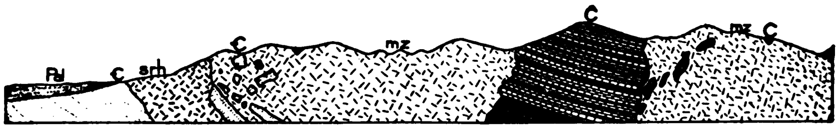

FIG. 249.—Section showing the relations of the Carboniferous system at one point in the vicinity of Tintic, Utah. Ꞓ (Tintic quartzite) = Cambrian; *C* (Mammoth limestone) = Carboniferous; *mz* (monzonite) and *srh* (rhyolite) = igneous rock; *Pal* = alluvium. The section shows that much of the sedimentary rock was disturbed and displaced by the extrusion (or intrusion) of the lava. Length of section about 3 miles. (Tower, U. S. Geol. Surv.)

North of the United States, Carboniferous strata (largely Lower Carboniferous) outcrop on the west side of the northward continuation of the Great Plains,[5] and perhaps on the east. The strata of these belts are probably continuous beneath the younger strata which occupy the surface between them and they are probably also con-

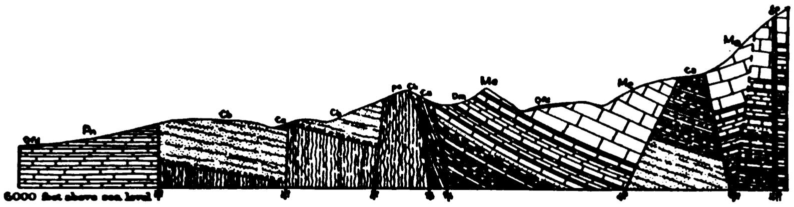

FIG. 250.—Structure near Bisbee, Ariz. *ps* = pre-Cambrian; *Ꞓb* and *Ꞓa* = Cambrian; *Dm* = Devonian; *Me* = Mississippian; *Ca* = Pennsylvanian; *Qfd* = Quaternary; *gp* = granite porphyry (Triassic or Jurassic). Length of section, a little more than one mile. (Ransome, U. S. Geol. Surv.)

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[1] Lindgren, Science, Vol. XIII, N. Ser. 1901, p. 271.

[2] Diller, Am. Jour. Sci., Vol. XV, p. 348, 1903.

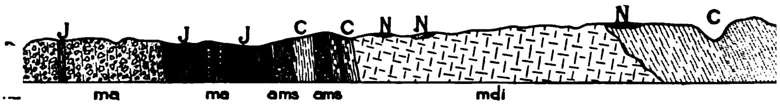
[3] Folios U. S. Geol. Surv., and King, Geol. Surv. of 40th Parallel, Vol. I.

[4] Smith, G. O. Mount Stuart, Wash., folio, U. S. Geol. Surv.

[5] Dawson, Science, March 15, 1901.

ous to the southward with the Carboniferous formations of tl ted States.

The system is widespread on both sides of the Gold range of Britis umbia. West of that range, the formations of the system (incluc



251.—Section showing the Carboniferous in the Sierras of central Californ (Calaveras formation) = Carboniferous; *J* (Mariposa slates) = Jurassic; *n* = metadiorite; *ams* = amphibolite schist; *N* = igneous rock of various sorts, eocene age. Length of section about 6½ miles. (Ransome, U. S. Geol. Sur

the Lower Carboniferous) contain much volcanic rock, the great of which was extruded before the close of the period. The igneo vity of the time extended northward beyond the boundaries ish Columbia into the little-known Northwest Territory,[1] a hward into the United States. The Pennsylvanian system[2] inued northward into Alaska, where it is less wide-spread than t issippian so far as present knowledge goes. In the arctic regio merica, the Mississippian and Pennsylvanian are not differentiat one or both are believed to be somewhat widespread. The sa ems also find meager representation in Mexico and Central Ameri

Sections of the Mississippian and Pennsylvanian Systems.

The following sections of the Pennsylvanian system (togetl the Mississippian and in some cases the Permian) at vari its within the United States, supplement those given in t endix and give some idea of the range, variations, and relatic e system:

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[1] Dawson, Science, March 15, 1901.

[2] Brooks, Professional paper, p. 19.

SECTION IN NORTHERN PENNSYLVANIA.[1]

	Names of Formations.	Thickness in Feet.	Characteristics.
Pennsylvanian.	Summit removed by erosion		
	Pottsville formation....	200	Sandstone, black shale, and fire-clay, with a three-foot coal-bed in the upper part.
	Sharon conglomerate....	60–100	White quartz conglomerate and sandstone.
	Unconformity.		
Mississippian.	Mauch Chunk shale.....	0–40?	Red shale.
	Oswayo formation...... (Lower part of Oswayo probably Devonian.)	1000 ±	Varicolored sandstone and shales.

SECTION IN SOUTHWESTERN PENNSYLVANIA.[2]

	Names of Formations.	Thickness in Feet.	Characteristics.
Permian.	Summit removed by erosion		
	Dunkard series.........	400 +	Blue to black limestone, weathering white; coarse sandstone at the base; contains a number of thin coal-beds.
Pennsylvanian.	Monongahela series.....	380 ±	Blue limestone with calcareous shale-beds; lentils of sandstone and coal; the most important coal-bearing formation in southwestern Pennsylvania, and contains the Pittsburg coal seam.
	Conemaugh series.......	590 ±	Chiefly red and green shales, with interstratified beds of coarse sandstone and thin beds of coal.
	Allegheny series...... ...	270 ±	Shales, sandstone, and three important coal-beds.
	Pottsville sandstone....	180 ±	Generally coarse hard sandstone or conglomerate, inclosing a thin irregular bed of shale; equivalent to the uppermost beds of the Pottsville formation in the type locality.
	Unconformity.		
Mississippian.	Mauch Chunk shale.....	250	Red and green shales with beds of greenish sandstone, inclosing a lentil of blue fossiliferous limestone, which is the thin edge of the Greenbrier limestone of Virginia.
	Pocono sandstone......	300 +	Sandstone, varying from thin-bedded flaggy rock to coarse irregularly bedded conglomerate; beds of silicious limestone at the top.
Devonian.			

Strata in broad gentle folds.

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[1] Fuller, Gaines (Penn.) folio, U. S. Geol. Surv.

[2] Campbell, Masontown-Uniontown (Penn.) folio, U. S. Geol. Surv.

GENERALIZED SECTION FOR WEST VIRGINIA.[1]

Names of Formations.	Thickness in Feet	Characteristics.
Dunkard series.........	1020	Red shales, massive sandstones, thin li stones, and a few thin beds of co rocks slightly gypsiferous; fresh-wa deposits.
Monongahela series.....	381	Much limestone; a little red shale; so massive sandstones, one of which is the uppermost " oil sand " yet develo in the Appalachian field; five coal-be the most important of whichis the Pi burg seam; Permo-Carboniferous flo fresh-water fauna.
Elk River series or Barren Measures......... (Corresponds to Conemaugh series.)	584	Much red shale in upper two thirds; Per Carboniferous fauna and flora; t limestones, three or four thin coal-be several important sandstone beds, of which carry oil. Lower half of se of marine or littoral origin.
Allegheny (including Kanawha) series.....	264	Dark shales and gray sandstones, with important coal-beds and two or th thin beds of limestones; one oil and horizon; marine fossils; typical (Measures flora.
Pottsville conglomerate. Unconformity.	200–1500	Massive pebbly sandstones, usually bea salt water; separated by dark sh which hold thin coal seams at the no and important ones at the south.
Mauch Chunk shales. ...	150	Soft red shales interstratified with gr sandstones and impure limy beds. Se thins and disappears westward; thi ness given is for Monongahela Marion Counties.
Mountain or Greenbrier limestone............	90	Hard gray limestone.
Pocono sandstone......	200	Big Injun oil sand, including Keener sa horizon at the top; one of the m important oil and gas horizons in State.
evonian.	380	Shales and sandstones, including Smi Ferry oil sand, and possibly Berea.

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[1] White, West Virginia Geol. Surv., Vol. I, p. 212. The section for Marylan similar to the above. See Prosser, Jour. of Geol., Vol. IX, pp. 422–429.

SECTION IN WESTERN VIRGINIA.[1]

	Names of Formations.	Thickness in Feet.	Characteristics.
Pennsylvanian.	Summit removed by erosion.		
	Wise formation	100+	Shale, sandstone, and coal-beds.
	Gladeville sandstone	100	Coarse sandstone, locally conglomeratic.
	Norton formation	1200–1300	Shale, sandstone, and coal-beds; the important coal-bearing formation of the region.
	Lee formation	1500±	Coarse massive conglomerate; shale with coal-seams; sandstone, generally free from pebbles, with shale layers; shale with coal-seams; massive sandstone.
	Unconformity.		
Mississippian.	Pennington shale	1040–1100	Red and green argillaceous shale; occasional beds of sandstone and impure limestone.
	Newman limestone	1000±	Calcareous shale with beds of impure limestone; heavy-bedded, blue limestone, slightly cherty toward the base.
	Grainger formation. The lower part of this formation is Devonian.	1000–1500	Argillaceous and calcareous shale; sandy shale, and thin-bedded sandstone.

Strata folded and faulted.

SECTION IN SOUTHERN WEST VIRGINIA AND WESTERN VIRGINIA.[2]

	Names of Formations.	Thickness in Feet.	Characteristics.
Pennsylvanian.	Upper part wanting.		
	Charleston sandstone	500+	Coarse sandstone with beds of coal.
	Kanawha formation	1000±	Sandy and argillaceous shales; soft sandstone, and numerous seams of coal, many of workable thickness.
	Guyandot sandstone	10–100	Coarse sandstone or conglomerate (lentil).
	Harvey conglomerate	0–50	Massive conglomeraate (lentil).
	Sewell formation	650–700	Sandy and argillaceous shale and sandstone.
	Raleigh sandstone	300	Coarse sandstone in heavy beds.
	Quinnimont shale	300	Shale with thin beds of sandstone and a few coal-seams; Quinnimont coal-bed.
	Clark formation	380	Sandstone with some shale and coal-beds.
	Pocahontas formation	360	Pocahontas (No. 3) bed of coal; gray and green argillaceous sandstone and shale.
Mississippian.	Bluestone formation	800	Purple shale and thin red sandstone, with calcareous beds, sometimes taking the form of limestone conglomerate.
	Princeton conglomerate.	40	Coarse sandstone or conglomerate; calcareous matrix locally.
	Hinton formation	1250–1300	Purple shale, green and purple sandstone, and impure limestone or calcareous shale.
	Bluefield shale	1250–1350	Blue limestone and calcareous sandstone; calcareous shale.
	Greenbrier limestone	1500	Alternating shale, and heavy-bedded, blue fossiliferous limestones; heavy beds at base carry black chert.
	Pulaski shale	20–300	Bright red or purple.
	Price sandstone	200–300	Coarse yellow sandstone interbedded with sandy shale and coal-beds.

Strata gently folded.

[1] Campbell, Bristol, Va.-Tenn. folio, U. S. Geol. Surv. Unconformity between the Pennington and Lee formations is implied, but not affirmed, in the text of this folio.

[2] Campbell, Pocahontas, Va.-W. Va. folio, U. S. Geol. Surv.

SECTION IN EAST-CENTRAL KENTUCKY.[1]

Names of Formations.	Thickness in Feet.	Characteristics.
Summit removed by erosion.		
Corbin conglomerate....	90	Coarse pink sandstone or conglomer (lentil).
Unconformity.		
Lee formation..........	250–300	Shale and sandstone with coal-beds; o crops of coal are of limited extent; re on Pennington shale in places.
Rockcastle conglomerate lentil		Coarse conglomerate, unconformable on Pennington shale or on Newman limesto
Unconformity.		
Pennington shale	0–90	Red and green, with thin beds of limesto
Newman limestone.....	100–200	Blue, slightly cherty near the base.
Waverly formation.....	350–420	Fine green shale with iron concretic green, calcareous, and argillaceous sa stone.
Devonian.		

rata nearly horizontal.

SECTION FOR OHIO.[2]

Names of Formations.	Thickness in Feet.	Characteristics.
ian.		
Dunkard series.........	525	Sandstone, generally massive; shales, li stones, and thin coal-beds; beds n marine at least in part.
Monongahela series.....	200–250	Shales, limestones, and sandstones; im tant coal-beds.
Conemaugh series.......	400–500	Upper part mainly shales; lower part sa stones, with some shale and limesto
Allegheny series........	165–300	Shales, limestones, and sandstones, v important coal-beds.
Pottsville conglomerate..	250 ±	Light-colored sandstones and conglomera with some shale and a few coal-beds.
Unconformity.		
Maxville limestone......	25 ±	Fossiliferous limestone, often brecciated
Logan group...........	100–150	Sandstone, massive conglomerate, and sh
Black Hand conglomerate.................	50–500	Sandstone and fine conglomerate.
Cuyahoga shale........	150–300	Light-colored, argillaceous, with thin sa stone bands; shales contain ferrugin nodules.
Sunbury shale..........	5–30	Black bituminous shale.
Berea grit.............	10–135	Sandstone, important for building purp and for grindstones; locally a reposit for oil, gas, and brine.
Bedford shale..........	50–150	Thin-bedded shales, with occasional t beds of sandstone.
Devonian.		

rata dip at low angles.

ampbell, Richmond (Ky.) folio, U. S. Geol. Surv.

rosser, Jour. of Geol., Vol. XI, pp. 520–521; Orton, Geol. Surv. of Ohio, Vol. 3–39.

SECTION IN NORTHERN MISSOURI.[1]

Names of Formations.			Thickness in Feet.	Characteristics.
Pennsylvanian.	Missouri Series.	(Not subdivided)......	1000	Shales and limestones, the former predominant.
			150	Shale and sandstone.
			90	Shale and limestone.
			100–400	Shale and sandstone.
	Des Moines Series.	Pleasonton shales......	150	Shale and sandstone; occasional thin beds of concretionary limestone, and one or two thin beds of coal.
		Henrietta formation...	90	Shales, resistant limestones, sandstones, and clays; one or two beds of coal of commercial importance.
		Cherokee shales.......	100	Conglomerate at the base, grading into sandstone above and this into shale; coal-beds and occasional beds of limestone of limited extent.
		Unconformity. **Discontinuity.**		
Mississippian.	Kaskaskia.	Kaskaskia limestone. ..	200	Thin beds of gray limestone and bluish marl, rich in fossils.
		Aux Vases sandstone...	80	Fine-grained ferruginous.
	St. Louis.	St. Genevieve limestone	50	Thick-bedded.
		St. Louis limestone....	150	Heavy-bedded, gray, oölitic at base.
		Warsaw formation.....	80–100	Gray and bluish-gray limestone; fossils numerous.
	Augusta.	Keokuk formation.....	50	Limestone, massive, compact, white in color and highly fossiliferous.
		Discontinuity.		
		Upper Burlington limestone..............	50	Thin-bedded at the top, more massive, encrinital below; cherty.
		Lower Burlington limestone..............		White, bluish or brown in color; heavy-bedded; largely encrinital.
		(Unnamed)...........	9	Yellow, massive or thick-bedded, rather soft, fine-grained limestone.[2]
	Kinderhook.	Hannibal shales.......	72	Green, sandy above; brown, sandy, grading into soft sandstone.
		Louisiana limestone....	48	Buff to gray, compact, fine-grained in thin layers; similar to lithographic stone in texture.
Devonian.				

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[1] Pennsylvanian section is generalized for the northern part of the state; Mar-ut, Missouri, Geol. Surv., Vol. XII, pp. 267–269. The Mississippian section, above he Keokuk, is for St. Genevieve Co.; Shumard, Geol. Surv. of Missouri, 1855–71, p. 292–293, and Keyes, Missouri, Geol. Surv., Vol. IV, p. 48. Below the Keokuk, he section is that exposed at Louisiana, Mo.; Proc. Iowa Acad. Sci., 1896, Vol. IV, p. 26–27.

[2] This bed has been correlated with the Chouteau limestone which is well leveloped in central and southwestern Missouri, but this correlation is probably ncorrect.

SECTION IN ARKANSAS.[1]

	Names of Formations.	Thickness in Feet.	Characteristics.
	Potean beds.	3500	Not described in detail.
	Productive beds..	1800	Mainly shales and sandstones with some coal-beds.
	Barren beds.	18480	
	Discontinuity.		
	Millstone grit.	500	Sandstones and conglomerates; friable to hard and compact; buff or brown; occasionally thin seams of limonite.
Boston series.	Kessler limestone.	3–15	Thin-bedded.
	Coal-bearing shale.	60–90	Highly fossiliferous; coal seams 6–14 inches thick.
	Pentremital limestone. .	0–90	Impure, dark-colored, loose-textured; sometimes interbedded with sandstone.
	Washington sandstone and shale.	40–75	Sandstone and gray shale in varying proportions.
	Archimedes limestone. .	0–80	Light gray limestone, rich in Archimedes.
	Marshall shale.	0–250	Black, bituminous shale.
	Batesville sandstone. . .	10–200	Sandstone, sometimes massive cross-bedded in places.
	Spring Creek black shale and limestone.	300	Black to bluish or yellowish brown in color.
	Wyman sandstone.	0–9	Sandstone, rather soft.
	Boone chert (including St. Joe marble).	370	Interbedded strata of chert and limestone in varying proportions; contains St. Joe marble, 25–40 feet.
	Sylamore sandstone. . . .	0–40	Hard or saccharoidal sandstone and thin-bedded black shale; phosphates.
	Eureka shale.	0–50	
	Unconformity.		
ilurian.			

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[1] he section above the Millstone Grit is for the Arkansas River valley; that below, e northern part of Arkansas. Adams, 22d Ann. Rept., U. S. Geol. Surv., Pt. II, -89; Simonds, Ark. Geol. Surv., Ann. Rept. 1888, Vol. IV, pp. 26–106; Hopkins, 1890, Vol. IV, pp. 90–94, 253; Penrose, ibid. 1890, Vol. I, pp. 129–139; Williams, 1892, Vol. V, pp. 273–322; Branner, Am. Jour. Sci., 4th series, Vol. II, 1896, .

SECTION IN NORTHERN TEXAS.[1]

	Names of Formations.	Thickness in Feet.	Characteristics.
Pennsylvanian.	Albany division.	0–1180	Thick beds of limestone, generally separated by shaly layers.
	Cisco division.	840	Shales, with thin beds of limestone, sandstone, conglomerate and coal.
	Canyon division.	800–930	Limestone and shale with local beds of sandstone and conglomerate; no coal.
	Straw division.	950–3700	Sandstone and shale; no coal.
	Millsap division.	1000	Blue and black shale interstratified with occasional limestone and sandstone strata.
	Ordovician?		

SECTION IN WEST-CENTRAL COLORADO.[2]

	Names of Formations.	Thickness in Feet.	Characteristics.
	Jura-Trias		
	Unconformity.		
Pennsylvanian.	Maroon conglomerate	2500	Conglomerate and sandstone in heavy beds; material is derived chiefly from the Archean, but some of the conglomerate contains limestone pebbles derived from the Mississippian beds; occasional thin beds of fossiliferous limestone.
		2000	Quartzose conglomerate, grit and sandstone, with varying amounts of pebbles derived from the Weber and Leadville formations, sometimes forming the bulk of the deposit; thin interbedded layers of fossiliferous limestone.
	Faunal break.[3]		
	Weber limestone.	100–550	Dark gray to black shale, with limestone beds carrying black chert.
	Unconformity.		
Mississippian.	Leadville limestone.	400–525	The upper third massive, blue and cavernous; lower two thirds bedded gray to brown; dark cherts.
	Silurian.		

Rocks faulted and somewhat folded.

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[1] Cummins, Geol. Surv. of Texas, 2d Ann. Rept., pp. 361–375.

[2] Eldridge, Anthracite-Crested Butte (Colo.) folio, U. S. Geol. Surv.

[3] Girty, Professional Paper No. 16, pp. 258–267.

The Coal.

he general conditions under which sandstone, shale, and lime- originate have already been stated, and need not be here repeated, in the discussion of the formations of the preceding periods there been no occasion to consider the formation of coal. From its omic importance, this sort of rock has been studied with more than most others, and geologists are agreed, in a general way ast, as to its mode of origin.

rigin.—There is no doubt that the coal is of vegetable origin. pt by the accumulation of vegetable matter, no way is known hich such beds of carbon could be brought into existence. Furnore, the coal and its associated shales contain abundant remains ants, and sometimes even recognizable tree-trunks, in the form of and microscopic study has revealed the remarkable fact that the itself, even the hardest anthracite, is often but a mass of altered, gh still recognizable, vegetable tissues. Concerning the exact ıer in which the beds of vegetable matter accumulated, there me difference of opinion, and concerning the conditions under h it was converted into the various sorts of coal, there is still .[1]

uch of the coal is essentially pure, containing little matter of sort which was not in the plants which gave origin to it. Purity not mean freedom from ash, since mineral matter, which on ustion becomes ash, is present in all plants.[2] Along with the amount of coal which is pure, or nearly so, there is much which ins some admixture of earthy matter. Where the admixture rthy matter is small, the coal may still be used; but from poor of this sort, there are all gradations into carbonaceous shale, the ntage of carbon becoming so low as to show itself only in a black . Black shales are common associates of coal-beds.

he purity of many coal-beds, not only locally but over great areas, s to warrant the conclusion that such beds were made of vegeta- which grew where the coal now is. The vegetation concerned was land or swamp vegetation. Had it been washed down from the land where it grew into the situations where the coal is, and apparently there is no other way in which it could have been drifted together, it should have been mixed with earthy sediment, and the product, even where the vegetable matter had undergone the necessary changes, would have been very unlike the purer coal-beds now known. Furthermore, the nearly uniform thickness of many of the coal-beds over great areas, sometimes many thousand square miles, constitutes a strong objection to the hypothesis that it was drifted together by any process whatsoever.

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[1] iscussions concerning the origin of coal are to be found in many of the geological s of the States where coal occurs, notably Ohio, Pennsylvania, Illinois, Iowa, uri, and Arkansas.

[2] any of the modern allies of the coal-plants contain as much as five per cent h, and some as much as twenty.

In support of the theory that the vegetation grew where the coal-beds now are, many facts, in addition to the purity and the uniformity of thickness already cited, may be noted. Thus (1) beneath each coal-bed there is, as a rule, a layer of clay often filled with roots in the position of growth. The clay seems to have been the soil in which the coal vegetation was rooted in the earliest stages of the accumulation. (2) In association with the coal-beds, the stumps of trees are sometimes found still standing as they grew (Fig. 252). (3) In the coal-beds, or in the associated layers of shale, imprints of the fronds of ferns are found. They are often so numerous and their forms so perfect as to indicate that they were buried where they fell, rather than

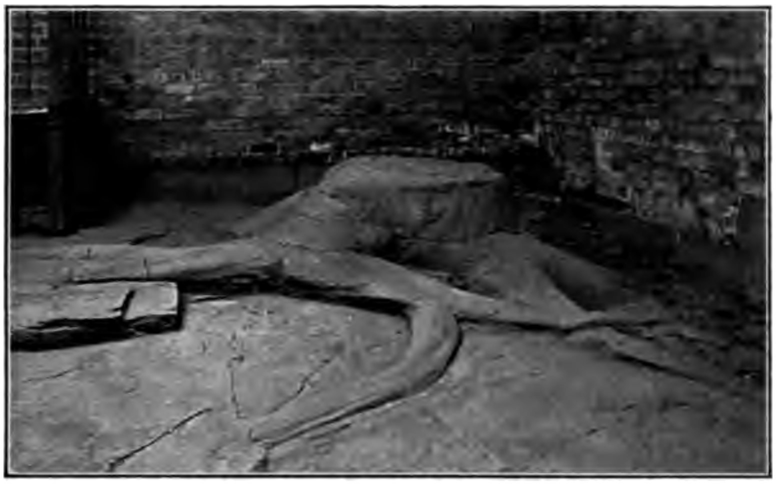

FIG. 252.—Showing a stump standing as it grew in Coal Measures near Glasgow, Scotland.

they were drifted by moving waters from one place to another. he layer of rock next overlying a coal-bed often contains abundant ins of vegetation, especially in its lower part, as if the condi- which brought about its deposition resulted in the destruction e forest growths which had preceded. In such situations, trunks es 50 and 60 feet long, and 2 or 3 feet in diameter, are sometimes l. (5) The vegetable matter in and about coal-beds is made the trunks, small stems, leaves, and fruits of the various plants rned, intermingled in such manner as to indicate that the vegeta- grew where the coal now is. The drifting together of vegetation, it would not have completely separated these various constitu- one from another, could scarcely have left them commingled as are now found.[1]

hile it is confidently believed that most of the workable coal sents the growth of vegetation *in situ*, it is not to be understood coal was never formed from vegetation which drifted together, t " drifted " vegetation never entered into the formation of coal. me of the small coal-basins of France, much vegetation washed from the land is said to have entered into the coal,[2] and the may be true elsewhere.

e have now to inquire in more detail concerning the conditions which the coal-beds were formed. The things to be accounted re three: (1) The conditions under which the necessary bodies getation accumulated, often essentially free from the admixture liment; (2) how it was kept from decay; and (3) how it was ged into coal.

vamps and marshes are the only places where vegetal matter w accumulating in quantity, with little admixture of sediment. e swamps are large, or where their surroundings are sufficiently o prevent the inwash of sediment, vegetation is accumulating, taminated with any notable amount of sand or mud. In the es along some parts of the Atlantic coast, for example (Fig. 253), are great quantities of vegetal matter which is locally mixed little sediment. Likewise in Dismal Swamp, vegetable matter,

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or expositions of the theory that the coal-plants grew where the coal is found, gan, Trans. Geol. Soc., VI, 1842, p. 495; Newberry, Am. Jour. Sci., XXIII, p. 212, and Geol. of Ohio, Vol. II, p. 125.

eikie, Text-book of Geology, 3d ed., p. 808.

essentially free from sediment, and composed of the trunks, branches, leaves, and fruits of the trees, shrubs, and herbs which grow there, has been long accumulating, and its mass is now great. In various cypress swamps, too, great thicknesses of vegetable matter are found, essentially free from foreign matter. The same is true of mangrove swamps, which differ from the cypress swamps in that they spread into salt water. The multitude of marshes and peat-bogs in the United States and Canada are further illustrations of the accumulation of vegetable matter, sometimes mixed with abundant sediment and sometimes nearly free from it.

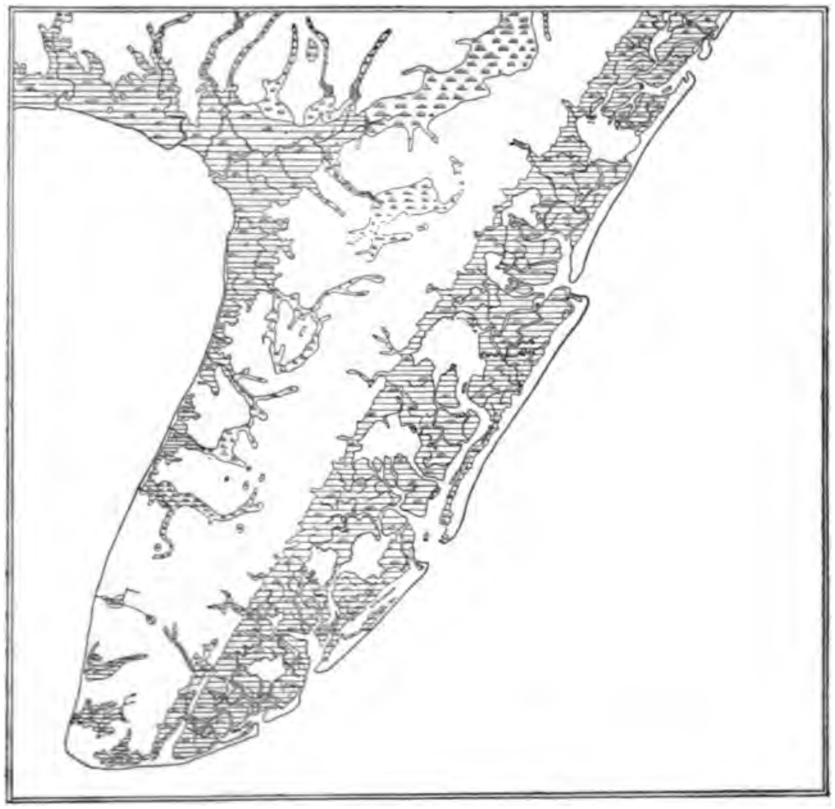

FIG. 253.—Map of the Cape May peninsula, showing coastal marshes. The unshaded areas inside the coast line are dry land.

The vegetation in such situations need not be more luxuriant than ioist lands which are not swampy. On fertile prairies and in forests the annual growth of vegetation is great; but as the s, fruits, twigs, and trunks fall, they decay, and the larger part ir substance is returned to the atmosphere. If the decay of vegeta- does not keep pace with its growth and death, an undecayed rtially decayed residuum of organic matter remains, giving the black color. It is a matter of common knowledge that black re more common in moist regions than in dry ones, in cool regions in warm ones, and on flat surfaces than on sloping ones. In a region there is more growth (and therefore more death) of vege- than in a dry one, and a better chance that decay will not keep with death. Decay is less rapid in a cool climate than in a hot o the former is more likely to have a residuum of partially decayed ic matter. From a flat surface the undecayed organic matter likely to be removed by erosion than from a sloping one, and oorer drainage has the effect of greater moisture. Forests, by ng the ground and checking the drainage, have the effect of addi- moisture.

n increasing blackness of the soil may often be observed as the rs of a marsh are approached. The increase in blackness means rease in the amount of undecayed or but partially decayed organic r, and this in turn appears to be immediately connected with ncreasing moisture of such situations. In the marshes them- where the vegetation falls into water, it usually undergoes decay only, and not that type of decay suffered by the vegeta- which falls on drier lands. The preserving influence of water n in many ways. Posts and piles set partly in water, and above, decay just above the water-level, while the portions remain sound. It is the preservation of organic matter in the of marshes and very shallow lakes which converts them into bogs, for the peat is nothing more than accumulated vegetable r undergoing those changes to which vegetable matter in water ject.

the surroundings of a marsh be low, little sediment is washed it, and there is every gradation from the earthy soil about it, y colored by organic matter, to the deposit in the marsh itself, chiefly of organic matter. Given continued favorable condi- and the organic matter of a bog may become very deep, as it now is in Dismal Swamp, and in many other less well-known swamps and bogs. In and about marshes and swamps we therefore find the conditions for the accumulation of considerable thicknesses of vegetable matter, essentially free from sediment, and at the same time the conditions which keep it from decay.

But while the vegetable matter is not destroyed, it is not preserved intact. The composition of wood and peat are illustrated by the following analyses (the ash is omitted), though it is not to be understood that either wood or peat has a constant composition. The difference, it will be seen, is not great.

	Carbon.	Hydrogen.	Oxygen.	Nitrogen.
Wood	49.66	6.21	43.03	1.10
Peat	59.50	5.50	33.00	2.00

The relative atomic proportions of carbon, hydrogen, and oxygen in wood are approximately expressed by the formula $C_6H_9O_4$. In the air, the carbon and the hydrogen of the wood unite with the oxygen of the air or of the wood itself, forming carbon dioxide and water, the principal products of the decay of vegetable matter. But under water, the atmospheric oxygen is largely excluded, and the elements of the wood unite with one another to a larger extent, while the oxygen of the air plays but a subordinate part. One of the common products of decay under such circumstances is CH_4 (marsh-gas), which bubbles up from many swamps and escapes into the atmosphere. The formation of this gas, as its composition shows, exhausts the hydrogen four times as rapidly as the carbon. If the carbon of the wood unites with the oxygen of the wood, forming carbon dioxide, the oxygen is exhausted twice as rapidly as the carbon. If the hydrogen and the oxygen of the wood combine, the result is to increase still more rapidly the percentage of carbon remaining, so that in whatever way these elements combine, the result must always be to increase the proportion of carbon remaining in the solid. Even under water it is probable that atmospheric oxygen dissolved in the water takes part in the changes, and in so far as this is the case, the proportion of carbon remaining after the changes have taken place is diminished.

While the exact quantitative relations of the reactions which take place are not known, and are probably not constant, the following

[1] suggests certain changes which might take place, and also the ucts which would remain at certain stages of the process:

ood [2] (timber).... $C_{36}H_{54}O_{24} = 6(C_6H_9O_4)$

ubtract $\left\{\begin{matrix}8CO_2\\4CH_4\\6H_2O\end{matrix}\right\} = C_{12}H_{28}O_{22}$

nd there remains $C_{24}H_{26}O_2$ = about the composition of brown coal.

ood............. $C_{36}H_{54}O_{24}$

ubtract $\left\{\begin{matrix}6CO_2\\4CH_4\\10H_2O\end{matrix}\right\} = C_{10}H_{36}O_{22}$

nd there remains $C_{26}H_{18}O_2$, which falls within the range of bituminous coal.

ood............. $C_{36}H_{54}O_{24}$

ubtract $\left\{\begin{matrix}6CO_2\\6CH_4\\11H_2O\end{matrix}\right\} = C_{12}H_{46}O_{23}$

nd there remains $C_{24}H_8O$, which falls within the range of anthracite.

ince the changes above are changes which take place in peat- the altered vegetation there found appears to be a step on the from the ordinary forms of vegetable tissue to coal. The follow- able [3] shows the composition of wood, peat, and various types of From a comparison of this table with the preceding, it is not ult to understand how vegetable matter is converted into coal.

	Carbon.	Hydrogen.	Oxygen.	Nitrogen.
1. Wood...........	49.66	6.21	43.03	1.10
2. Peat.............	59.5	5.5	33.0	2.0
3. Brown coal.......	68.7	5.5	25.0	0.8
4. Bituminous coal..	81.2	5.5	12.5	0.8
5. Anthracite.......	95.0	2.5	2.5	0.0

the vegetable matter, after having been accumulated to great is and after having been partially altered, say to the condition at, were buried beneath beds of mud or sand, it would undergo er changes, both chemical and physical, tending to bring it nearer nearer to the condition of coal. The oxygen of the air would be more effectually excluded, and the chemical changes more

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fter Le Conte, Elements of Geology.

he composition of cellulose is usually given as $C_6H_{10}O_5$ or some multiple of this. hanges can be developed equally well from this formula.

e Conte, op. cit.

largely confined to the constituent elements of the vegetable matter. The weight of the sediment would compress the vegetable tissues, and it is believed that the result would be its ultimate conversion into coal. The various grades of coal, bituminous, anthracite, etc., are thought to represent different stages in the process of change.

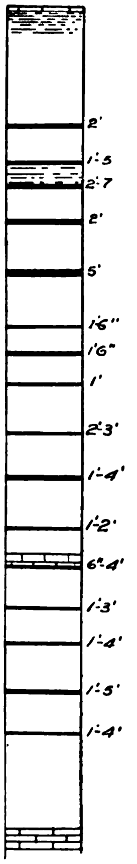
If the coal-beds represent the Carboniferous swamps, as they are believed to, we have still to inquire into the conditions under which swamps as extensive as the coal-beds existed, and to seek the explanation of their frequent recurrence (one for each coal-bed) in many regions.

The first condition for a swamp is lack of drainage, and the second a sufficient, but not an excessive amount of water. Enough to stop the growth of vegetation would be excessive, and too little to preserve it from ready decay after its growth and death, would be insufficient.

In the course of the widespread, but for the most part very gentle, movements which affected the eastern interior at the close of the Mississippian period, great areas appear to have emerged from the sea. Early in the Pennsylvanian period, considerable tracts which were not submerged stood so low as to be ill-drained or undrained, and constituted marshes. The conditions of climate and moisture appear to have been such as to allow the abundant growth of vegetation in the marshes. On falling into the shallow water, or upon the water-soaked bottom, the vegetable matter underwent changes of the nature indicated above. The ill-drained areas were thus converted into peat bogs, in which, in many places, little inorganic matter was mixed with the organic. The longer the life of the bog, the deeper the peat became. The rate of accumulation, though depending on climate and on the abundance of vegetation, is always slow. Under very favorable conditions, a foot of peat may accumulate in ten years or even less, but the usual rate is probably much slower. Peat bogs are now in existence in which the depth of the accumulated organic matter is 40 or 50 feet, but the length of time involved in the accumulation is not known.

Some of the great swamps probably came into existence along the sea-shores, and some in shallow basins or undrained areas remote from the sea, for fresh-water shells are found in association with some coal-beds, and marine fossils in association with others.

The history of a coal-bed.—Each coal-bed represents the accumulated vegetable growth of a long period. It would appear that rowth and accumulation of vegetation was often brought to an by subsidence which let the water (sea or lake or aggrading n) in over the marshes, drowning the plants, and burying the organic ɜr which had already accumulated, under deposits of mud, sand, or shells which the submergence brought in its train. A second coal-bed in the same region points to the recurrence of swamp conditions, and means either (*a*) that after submergence and burial of the organic matter, slight emergence ensued, caused by land or water movement, thus reproducing the conditions for bogs; or (*b*) that by sedimentation the sea or lake bottom where the first bog had been, was built up to the water-level, restoring swamp conditions. On the former hypothesis (*a*), two successive coal-beds would represent the following sequence of events: (1) A more or less static condition with the surface ill-drained, during which the vegetable matter accumulated; (2) a subsidence of the land or a rise of the water during which the vegetable matter was buried by sediment; (3) a reverse change, bringing the surface again to the condition which it occupied in the first place; (4) a later submergence, effecting the burial of the later growth of vegetation. On the second hypothesis mentioned above (*b*), but one movement is demanded. Stages (1) and (2) would have been as above, but the sedimentation of (2) continued until the swampy condition of the region was reproduced as a result of aggradation. The burial of the vegetation calls for further submergence. In other words, the first hypothesis calls for oscillation of level; the second, for successive movements of one phase only.



54. — Generalized on of the Coal sures in Kentucky. l thickness about feet. The heavy k lines = coal. wood, U. S. Geol. .)

ie number of coal-beds is often great. In Pennsylvania it fre-ly (but not everywhere) exceeds 20; in Alabama, 35 (not all ible) have been enumerated; in Nova Scotia, the number, includ-me dirt-beds, is said to be about 80; but in the Mississippi basin west of the Appalachians, the number is often less than a dozen (Figs. 254 to 257). Thus in Illinois the number of workable beds is nine.[1]

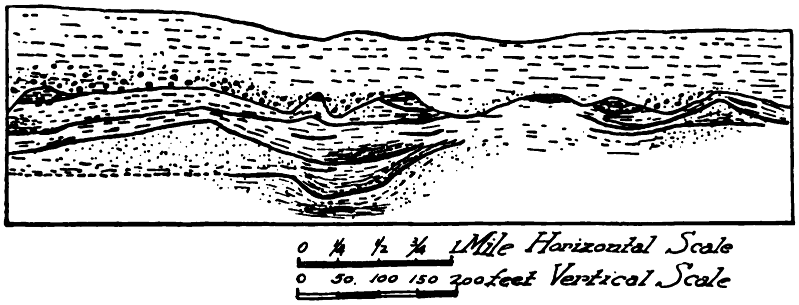

0 ¼ ½ ¾ 1 Mile Horizontal Scale
0 50 100 150 200 feet Vertical Scale

FIG. 255.—Section showing coal beds (heavy black lines) in Bay County, Mich., Amelith shaft. (Lane, U. S. Geol. Surv.)

If the foregoing sequence of events was repeated for each coalbed, it is manifest that the surface of great areas of the continent or else the surface of the sea, was in an unstable attitude during the Carboniferous period. The second hypothesis (*b*) has the merit (so far as it is a merit) of greater simplicity than the first, but is probably not applicable to all cases. The fact that local unconformities abound in the Coal Measures (Ind., Ill., Ia., *et al*, Figs. 258 to 260) shows that the surface was locally out of water and subject to erosion at various times and places in the course of the period. This points to changes in the relative level of land and water (partly the sea and partly land waters), though it does not show which was the changeable element. When it is remembered that many relative changes of level may have taken place without giving origin to coal seams, it is not too much to say that the number of fluctuations in the relative level of land

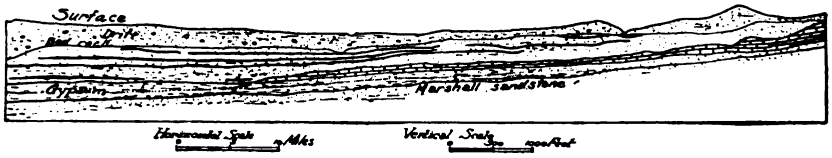


FIG. 256.—Section showing coal belt (heavy black lines) along the Pere Marquette Ry., Mich., east from Alma. (Lane, U. S. Geol. Surv.)

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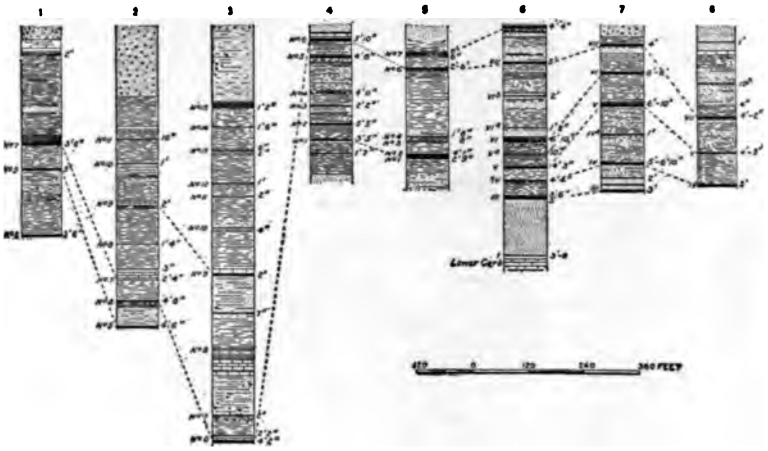
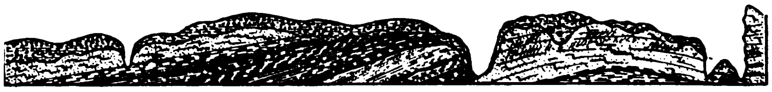
[1] Reports on coal have been published by all States containing coal, where there have been surveys. For local details see reports of Pennsylvania, Ohio, Kentucky, Tennessee, Alabama, Indiana, Illinois, Iowa, Missouri, Arkansas, Kansas, and Texas.

water in the eastern part of North America during the Penn-
nian period, was great, though perhaps not greater than during
r periods.



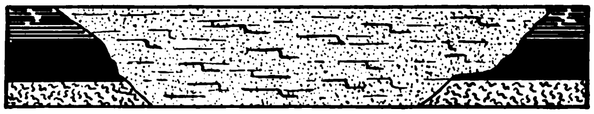
**257.—Sections of Illinois and Indiana Coal Measures; 1, shaft at Oglesby, La
lle Co., Ill.; 2, air shaft at Decatur, Macon Co., Ill.; 3, shaft at Kinmundy,
arion Co., Ill.; 4, boring at Galum Creek, Perry Co., Ill.; 5, boring at Danville,
ermilion Co., Ill.; 6, connected section from South Vermilion and Parke Cos.
d.; 7, connected section from Dugger and Linton, Sullivan and Parke Cos.,
d.; 8, connected section from Henderson, Ky., and Evansville, Ind. (Ashley,
. S. Geol. Surv.)**

xtent and relations of coal-beds.—The widespread distribution
oal does not mean that any one marsh necessarily covered the



258.—Local unconformity in Coal Measures of central Iowa. (Keyes, Ia. Geol. Surv.)

le of any one great coal-field. Some of the coal-beds, however,
known to be of great extent. Thus a single bed, the Pittsburg,



259.—Local unconformity in the Coal Measures; sandstone occupying "cut
t" in coal beds. Smoky Hollow mine, Marion Co., Ia. (Keyes, Ia. Geol. Surv.)

nown to be workable over an area of some 6000 square miles[1] in western Pennsylvania, Ohio, and West Virginia, and to have at least an equal extent where too poor to be generally worked. Many coal beds, on the other hand, do not occupy great areas. From their thicker portions they thin out in all directions, often grading into black shale. From these facts it is inferred that within the general area of a coal-field there may have been islands and peninsulas above the marsh level. Such areas interrupted the continuity of the swamps then, and interrupt the continuity of the coal-beds now.

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[1] White, West Virginia, Geol. Surv., Vol. II, p. 166.

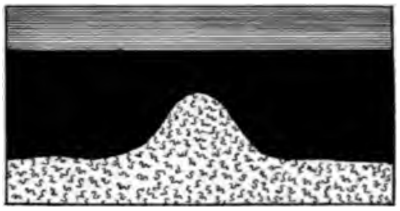

FIG. 260.—Irregularity in a coal bed showing a "horseback" in Craig Slope, Kalo, Ia. (Keyes, Ia. Geol. Surv.)

No parallelism between the coal-beds of different fields has been made out, and is not likely to be. Even within the same field the parallelism is by no means perfect, as shown by the fact that more seams are found in some parts of a field than in others. On the other hand, the larger coal-beds are often continuous over great areas, as already noted in the case of the Pittsburg bed.

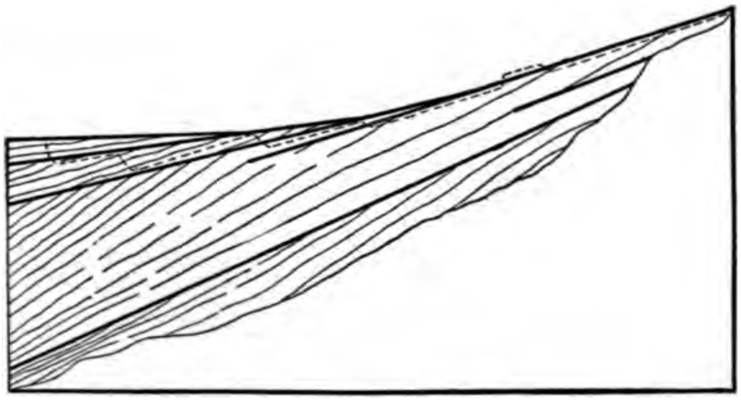

FIG. 261.—Bifurcation of a coal bed. The heavy black lines = coal. (Winslow.)

Traced laterally, a bed of coal is sometimes found to divide (Fig. 261) or, traced in the opposite direction, two beds are sometimes found to unite.[1] Fig. 262 suggests a possible sequence of events by which the rcation may be brought about. Vegetable matter for a coal seam ɔcumulating along *a-b* (*A*). The outer part of the bog then sinks so that sediment is deposited over a part of the area (*a* to *c*) re vegetation formerly grew. When the depressed area (*a* to *c*) ʒgraded or elevated (relatively) sufficiently (*C*), the bog is restored he left, and the two layers of organic matter at the left, unite at right, where the accumulation of vegetable matter has not been rrupted. It will be readily seen that other sequences of events ht bring about the same result, and that, if this process is fre-

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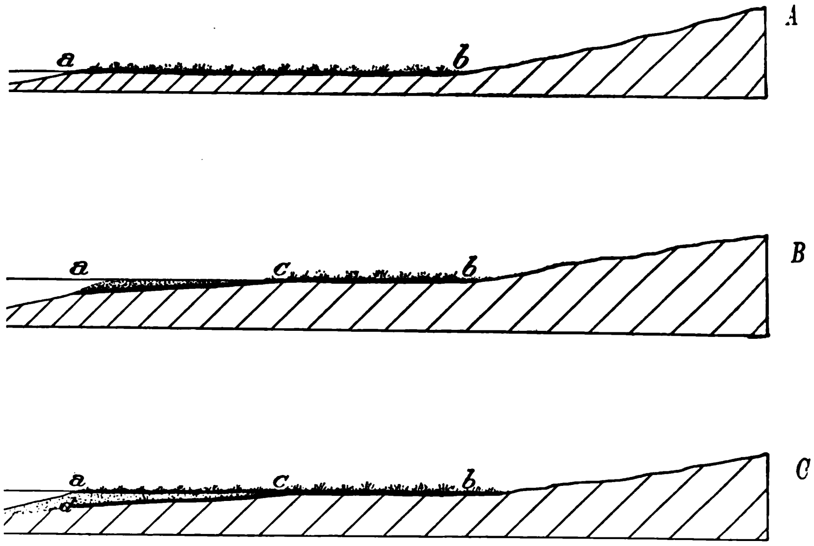
[1] The Nature of Coal Horizons; see Winslow, Geol. Surv. of Missouri, Preliminary Report on Coal, p. 25. Also Keyes, Jour. Geol., II, 178.



262.—Diagram illustrating the sequence of events which might lead to the bifurcation of a coal bed. In the first diagram, vegetal matter is accumulating from to *b*; in the second, a part of the area, *a* to *c*, is represented as submerged; in he third, the tract from *a* to *c* has been built up or lifted up (relatively) so as to ecome a marsh again, and vegetal matter is accumulating from *a* to *b*.

ntly repeated, great differences might exist in the number of coal ns in different parts of the same general region.

Varieties of coal.—The exact manner in which the different varie- of coal have arisen has never been satisfactorily determined. In ɔral it is true that the anthracite coal occurs in mountainous regions, re the coal and other layers of rock with which it is associated e been subject to more or less intense dynamic action. Thus, he mountains of eastern Pennsylvania (Fig. 263) the coal is mainly [illegible]thracite (Figs. 264–267), while in the central, and in most of the [illegible]estern coal-fields of Pennsylvanian age, where the strata are nearly horizontal or but slightly deformed (Figs. 255, 256 and 267 to 271), and altogether non-metamorphic, the coal is bituminous or soft. In Arkansas[1] where the strata have been subject to some, but not to extreme dynamic action, there is coal which is semi-anthracitic. Where the metamorphism of the associated rock has been extensive, the coal has gone beyond the anthracitic stage and has become graphitic. Thus in Rhode Island, where the strata have been highly metamorphosed, the coal is highly anthracitic, or even semi-graphitic.[2]

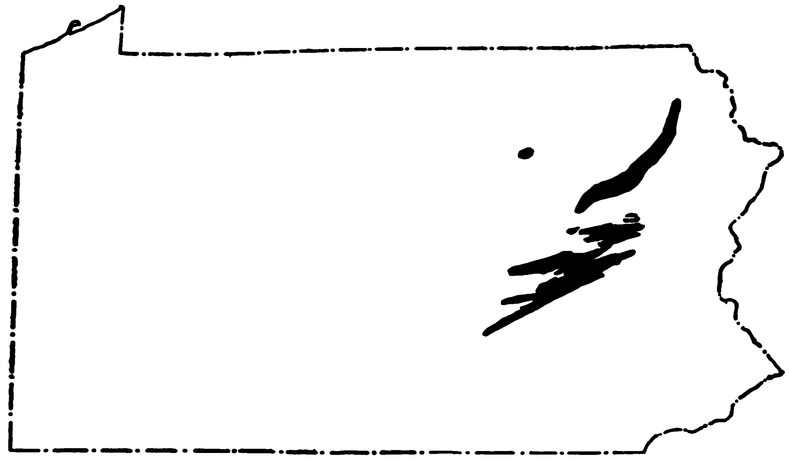


FIG. 263.—Map showing the areas of anthracite coal in Pennsylvania.

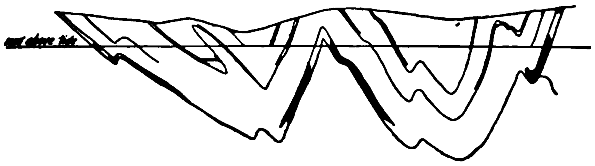


FIG. 264.—Section across Panther Creek basin in the anthracite region of Pennsylvania, showing the position of the strata and the coal beds. (Stoek, U. S. Geol. Surv.)

Anthracite coal is also found in some places (though not in the Coal Measures of the United States) in contact with dikes, in just the tions where other sorts of rock are metamorphosed. These omena long ago suggested that anthracite is to be looked upon

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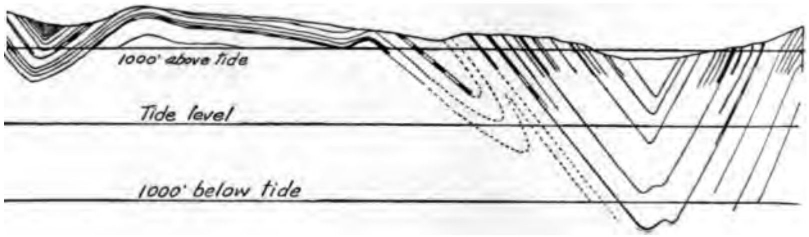
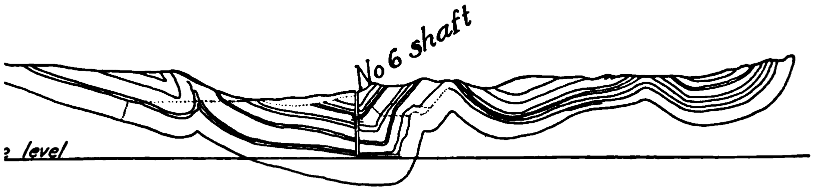
[1] Ann. Rept. Ark. Geol. Surv. 1888, Vol. III.

[2] Geology of the Narragansett Basin, Mono. XXXIII, U. S. Geol. Surv.



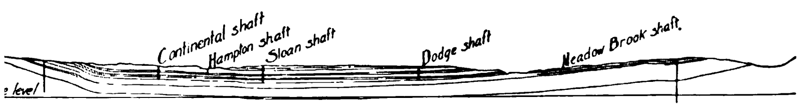
265.—Section of the Western Middle anthracite coal basin of Pennsylvania. ength of section, a little less than two miles. (Stoek, U. S. Geol. Surv.)

etamorphic coal produced from bituminous by processes similar me of those which induce metamorphism in other sorts of rock.



266.—Section south of Nanticoke, showing the position and relations of the al beds, in the Northern anthracite coal field. Length of section a little less an two miles. (Stoek, U. S. Geol. Surv.)

fact that metamorphic coal is usually found in regions where ion has exposed its beds (Figs. 264 to 267) has led to the conjec-



G. 267.—Section at Scranton. Length of section between 4 and 5 miles. (Stoek, U. S. Geol. Surv.)

that exposure may be a real factor in the problem, the exposure ring the escape of the volatile constituents, and so aiding in the sformation of bituminous coal to anthracite. Beds of bituminous are, however, often exposed in valley bluffs.

oth dynamic action, involving pressure and heat, and exposure ld seem to be conditions favoring the development of anthracite, it does not follow that these are the only factors in the problem, hat anthracite coal has never been produced in other ways. It

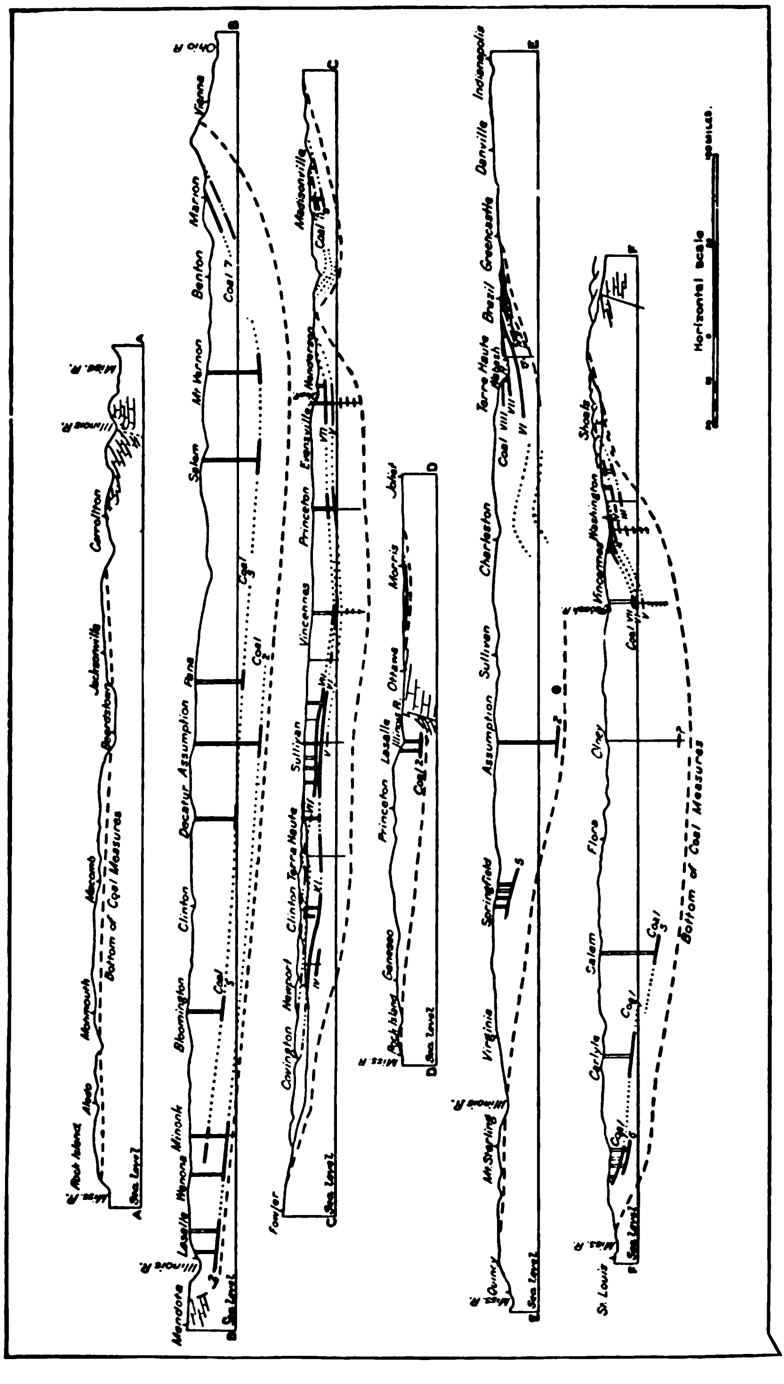
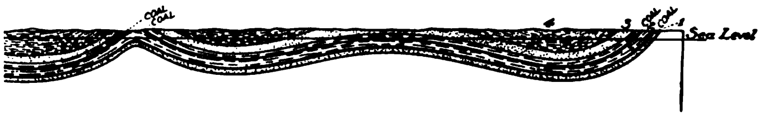


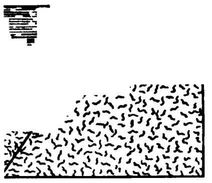
FIG. 208.—Showing the general structure of the Coal Measures in Indiana and Illinois. The names which appear on the sections show their location. (Ashley, U. S. Geol. Surv.)

been suggested that the anthracitic character of coal depends ıe length of time the vegetation was exposed before being buried



!69.—**Section showing positions and relations of the coal beds at a point in Indian rritory. The black lines indicate coal beds. Length of section about 11 miles. aff, U. S. Geol. Surv.)**

ther sedimentary rocks.[1] This seems to demand that thick beds ›al be more anthracitic at their bases than at their tops, or else the thin, slowly accumulated parts be more anthracitic than the :, faster-formed parts. Neither of these things seems to be gen-



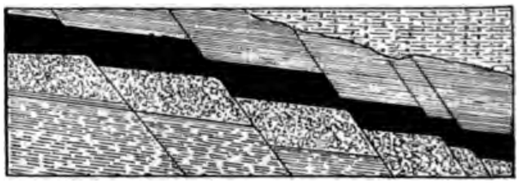


FIG. 270. FIG. 271.

!70.—Diagram showing slight faulting in the coal beds of Iowa. Bloomfield haft, Des Moines, Ia. (Ia. Geol. Surv.)

!71.—Step fault in Davidson mine, Jasper Co., Ia. (Ia. Geol. Surv.)

ɣ true, though the lower part of a coal-bed is sometimes "harder" the upper.

'ther varieties of coal appear to depend on the conditions to which ɩegetable matter was subject, either before or after burial, and ıe degree to which the bituminizing process has been carried.

Iron Ore.

he iron ore of the Coal Measures occurs in layers like the coal, the form of nodules which are often concentrated at a given hori- forming a nearly continuous layer. The ore is sometimes in orm of the carbonate of iron (siderite) and sometimes in the form ɩide. The iron is often associated with clay, making *clay iron-* . The iron ore of the Coal Measures seems to have been largely sited as a precipitate from the waters of inland and local basins, while the other members of the system were being laid down. Dissolved by the land waters from the soil and rocks, it was brought to the marshes in some soluble form. In the marshes, it was precipitated either in the form of the carbonate or ferric oxide. Subsequent oxidation has changed some of the original carbonate into ferric oxide. The principal iron ores of the Pennsylvanian system occur in Pennsylvania (Allegheny and Monongahela series) and eastern Ohio (Allegheny series).[1]

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[1] Stevenson, Jour. of Geol., Vol. I, p. 677.

General Geographic Conditions in the Eastern Interior.

Returning for a moment to the system of which the coal-beds form an inconsiderable part, it is to be noted that many of the clastic beds associated with the coal are known by their fossils to have been laid down in fresh water. Some of the occasional limestone-beds, on the other hand, as well as some of the clastic beds, were deposited where marine conditions prevailed. It follows that marine, lacustrine, and marsh conditions may also have alternated with the others, but such conditions, especially if the land be too low to suffer notable erosion, leave but indistinct records.

The succession of Pennsylvanian beds in southwestern Pennsylvania (Fig. 242) illustrates the great series of changes which took place in the sedimentation in the course of the period. These changes were probably the result of geographic changes, such as variations in the height of the land, the depth of the water, or in the areal relations of land and water, due to gradation. It is not to be inferred that changes were more frequent at this time than during other periods. Their record is conspicuous because of the coal; or, in other terms, because the land was near sea-level, so that extensive submergence and emergence resulted from slight changes of relative level of land and sea. It should be remembered that a series of equally frequent and equally extensive movements, or that equivalent degradation and aggradation, would leave no such record of themselves, if the surfaces concerned were well above or well below sea-level. It was the oscillation just above and just below water-level which allowed the record to be so clearly preserved. How far the oscillations were due to warpof the land, and how far to changes in the level of the sea, can- now be determined; but when we recall that the ocean-level , respond to every deformation which affects its bottom (unless pensated by an equivalent opposite movement), and to every stage lling,[1] it does not seem strange that its level is in a nearly per- al state of fluctuation.

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[1] For statistics concerning production of iron, see Census Reports (Vol. XV, 10th Census) and Mineral Statistics, U. S. Geol. Surv.

n general, it may be said that the movements of the crust which been of most importance, from the point of view of continental iological evolution, are not those which have affected high land eep sea bottom, but those which have converted sea bottom into , or land into sea bottom. Such changes are most likely to have n place where land was low, or water shallow. From the point ew of geology, therefore, *the critical level of crustal oscillation is the of the sea.*

Thickness.

he Coal Measures differ greatly in thickness in different sections e country, but, like all the preceding formations of the Paleo- they are especially thick in the Appalachian mountains, measured e usual method.

The thickness of the Millstone Grit (Pottsville conglomerate) , ranges up to 1700 feet in Pennsylvania, but it thins rapidly e westward. The Coal Measures are equally variable in thick- ranging from nearly zero to more than 3000 feet (Penn- nia to Alabama). In the interior, the corresponding formations y much exceed 1000 feet. In Ohio they are about 1200 feet ; in Indiana, 1000 feet; in Illinois, 1650 feet; in Michigan 300 and in Iowa, 600 feet. In Arkansas, the Coal Measures attain remarkable thickness of more than 20,000 feet,[2] from which it ferred that there must have been land close at hand capable of lying sediments in great quantity, combined, probably, with itions favorable to deposition in sloping attitudes. This was ably the axis of the Ouachita uplift. In Texas, the Penn- nian has a thickness ranging up to 5000 feet.[3] In the atch mountains, the Carboniferous strata (including the Lower oniferous) have been estimated to be about 13,000 feet thick, and in Nevada, 10,000 feet. In these regions, therefore, active deposition was in progress, and so far as the sediments are clastic, they were probably derived from the land area of western Nevada. For further details as to thickness, see the preceding sections, pp. 557–562.

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[1] Salisbury. Jour. of Geol. Vol. XIII. p. 469.

[2] Cited in Report of the Dept. of Geol. and Nat. Res. of Indiana.

[3] Richardson, Bull. G., Univ. of Texas Mineral Survey.

Duration of the Coal Measures Period.

So uncertain is our knowledge of the duration of geological time that all groups of data which can be made to throw light on the subject are of interest, even though they do not lead to trustworthy numerical conclusions. A vigorous growth of vegetation has been estimated to yield annually about one ton of dried vegetable matter per acre, or 640 tons per square mile. If this annual growth of vegetable matter were all preserved for 1000 years, and compressed until its specific gravity was 1.4 (about the average for coal) it would form a layer about six inches thick. But a large part of the vegetable matter, even in peat bogs, escapes as gas (CO_2, CH_4, etc.), in the making of coal. It has been estimated that three to four fifths of it disappears in this way. The six-inch layer would then be reduced to two tenths or to one tenth of a foot, and a layer one foot in thickness would require 5000 to 10,000 years. The aggregate thickness of coal is frequently as much as 100 feet, and sometimes as much as 250 feet. At the above rate of accumulation, and with the above proportions of loss, periods ranging from 500,000 to nearly 2,500,000 years would be needed for the accumulation of such thicknesses of coal.

It should be borne in mind, however, that much depends on the rate of growth of Carboniferous vegetation, which is not known. On the other hand, these figures refer to the coal only, not to the Coal Measures. The greater part of the Coal Measures is made up of shale and sandstone, and of these formations there are thousands of feet, even where the sediments were largely fine and their accumulation therefore probably slow. It would hardly seem unreasonable to conjecture that their deposition might have consumed an amount of time equal to or even greater than that demanded by the coal. This would double the above figures, making them something like 2,000,000 and 5,000,000 years respectively. These figures must be taken to mean nothing more than that the best data now at hand indicate that the Pennsylvanian period was a very long one.

Close of the Carboniferous Period.[1]

.fter the long period of oscillation above and below the criti recorded by the Coal Measures, the interior area east of the Miss was brought above the level of the sea, not to sink again benea .ring the Paleozoic era, and some of it at no later time. This upl :s at once the close of the Carboniferous, and the inaugurati .e Permian period. It is also probable that the deformative mo ;s which were to result in the folding and uplift of the Appalachi ntains began at this time. Dikes of igneous rock affect the C :erous strata of northwestern Kentucky and southern Illin the date of their intrusion has not been determined. It see .mprobable that it was during the general period of deformati h marked the close of the Paleozoic; but this is conjecture.

'here were also notable changes in the western half of the c it, for the strata of the Permian period are much less wi d than those of the Carboniferous. Where they occur, th titution and their fossils are such as to indicate not only differ ions of land and water, but different conditions of erosion, a bsence of the sea from some areas where deposition was in progr ne Sierras,[2] too, there seems to have been deformation and me phism of the Carboniferous beds at some time antedating ssic period. The exact date of the disturbance has not b ., but it may have been contemporaneous with that in the Ap an Mountain region.

n America, the Permian has usually been regarded as the clos ; of the Carboniferous. This classification seems best to fit of the eastern part of the continent, but when the relations ?ermian in other parts of the world are considered, it seems m .g to regard the Permian as a distinct period.

IN FOREIGN COUNTRIES.

Europe.

'eneral.—As in America, the oldest formation of the Upper C 'erous in Europe is often a conglomerate and sandstone formati Millstone grit, which in some parts of Britain attains a thickn

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[1] 'or general account of Appalachia during the Paleozoic Era see Willis, Surv., Vol. IV, pp. 23–88.

[2] ee description of the Gold Belt, in the late folios of the U. S. Geol. Surv.

of 5500 feet.[1] This formation has the same stratigraphical position, and probably the same significance as the formation of corresponding name (Pottsville, etc., see p. 539) in America.[2] It was indeed this correspondence which led to the adoption of the English name for the American formation. The thick Millstone grit of England is thought to represent a shore accumulation against a ridge of Paleozoic rock which crossed central England in the early part of the Carboniferous period. The ridge was later submerged, but not until some part of the Coal Measures had been deposited. North from this ridge the Millstone grit thins rapidly. The fossils of the Millstone grit are singular in that the plants resemble those of the Coal Measures above, while the animals are more like those of the Lower Carboniferous below.[3]

The formations of the western European Coal Measures, like those of eastern North America, consist principally of shales (and clays), with subordinate amounts of sandstone and limestone. Associated with these commoner sorts of rock, there are beds of coal and clay-ironstone, both of which occupy positions corresponding in all essential respects, with those of the similar formations in eastern North America. As in America, there are local unconformities within the system. The system contains workable coal in Great Britain, Ireland, Belgium, France, Spain, Germany, Austria, and Russia, but the total area of productive coal in Europe is much less than in America. In places in Wales, there are as many as 100 seams of coal, many of which are worked. In Belgium, and in some parts of Germany the number of coal-beds is also very large. In Westphalia the number of workable beds is said to be 90.[4] The aggregate (maximum) thickness of the coal in Lancashire is 150 feet; in Westphalia, 274 feet; in Mons (Belgium), 250 feet. In central and northern France there are more than 300 small areas where portions of the Coal Measures are found. Some of them contain remarkable thicknesses of coal.[5] The Coal Measures of central Europe are less wide-spread than the Lower Carboniferous in the same region. Coal-beds are numerous in the Coal ıures of Silesia, one bed attaining a thickness of 50 feet.[1] Heı lsewhere, beds of marine origin alternate with those which wε sited on land, in marshes, etc. The constitution of the systε ıch as to show that physical conditions corresponding to thc he Pennsylvanian period in eastern North America were wic ad in western Europe.

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[1] Geikie, Text-book of Geology, Vol. II, p. 1047.

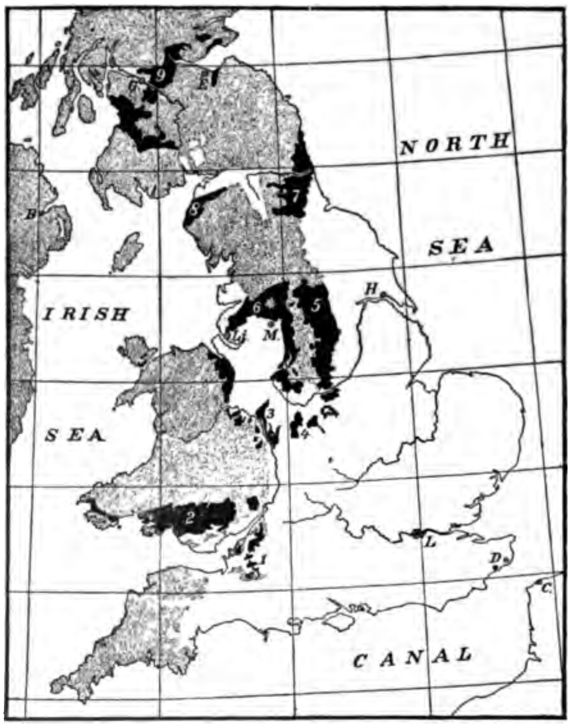
[2] The Millstone grit is sometimes regarded as the representative of a separate time-division coördinate with the Lower and Upper Carboniferous.

[3] Geikie, p. 1054.

[4] Idem, p. 1047.

[5] Idem, p. 1053.

t will be remembered that the coal-bearing part of the Carbo us series in America is confined to the eastern half of the contineı chief areas of productive Coal Measures in Europe are in the weste



ı. 272.—Sketch map showing distribution of coal in Great Britain (Kayser)

of the continent, another of the many rather striking correspc es between the formations in those parts of these contineı h border the same ocean. Fig. 272 shows the distribution in Great Britain, and 272*a*, in the Lower Rhine basin.

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[1] Idem, p. 1054.

southern Europe, the Lower and Upper Carboniferous are less distinctly separated.

In Russia, the two types of Carboniferous formations, the marine and the non-marine, are found, but not in the same relations as in the western part of the continent. Instead of the marine type below, and the lake-marsh-lagoon type above, the order seems to be so far reversed that the Lower Carboniferous contains most of the coal, while the Upper is made up chiefly of limestone. There is however much marine limestone in the Lower Carboniferous, and in southern Russia (Donetz coal-field) some coal in the Upper. The Upper Carboniferous limestone of Russia (Fusulina limestone) is represented by similar formations in southern Europe, where the system is more like that of eastern than that of western Europe. The faunas of the marine system in southern Europe, and of the marine part of the system in eastern Europe have much likeness to those of western North America, suggesting that marine life was able to pass between these continents, via northern Asia.

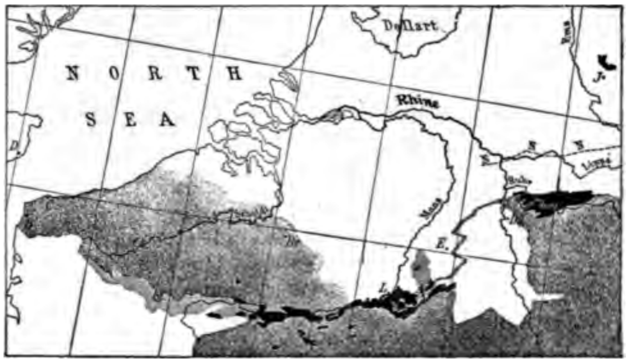

FIG. 272*a*.—Sketch map showing the position of the Carboniferous coal beds (black areas) in the lower Rhine basin (Kayser.)

The upper part of the Coal Measures system of Europe at various points and at various horizons contains bowlders, sometimes of large size, and beds of breccia or conglomerate of sub-angular fragments. The bowlders are of granite, gneiss, schist, quartzite, etc., and occur sometimes singly, and sometimes in groups. They have often been thought to represent deposits made by icebergs, and so to point to xistence of glaciers;[1] but this interpretation cannot be looked as established. Other interpretations, such as the transporta- of bowlders by uprooted trees floated out to sea, are tenable.

ough the Coal Measures are widely distributed on the continent, reas where they are exposed are relatively small, as compared those of America. It is not in all cases possible to say whether etached areas are the dissevered remnants of areas which were extensive, or whether they are but parts of areas which are still uous, though largely buried by younger beds. The system rs at the surface in relatively large areas in Belgium and northern e, and in small areas in southern France, and the Iberian penin- It is also known at many points in the mountain regions of al Europe, and has great development in Russia.

orth of the European continent, the Carboniferous formations lina limestone, Coral limestone, etc.) are represented in some e Arctic islands (Spitzbergen, Nova Zemla, Bear Island).

ickness.—The Coal Measures of Europe attain great thickness, 8000 feet (13,500 including the Millstone grit) thick in Lan- re, and several thousand feet in many parts of Great Britain Ireland. These extraordinary thicknesses of sedimentary rock eat Britain must mean the presence close at hand of somewhat sive and high land areas.[2] The corresponding strata attain a ness of 10,000 feet in western Germany, where they contain much

neous rocks and crustal disturbances.—The granites of the Harz, ngerwald, Black Forest, Vosges, and other mountains of central pe, appear to date from the end of the Early Carboniferous, h the eruptions probably continued into the Later Carboniferous. us sorts of igneous rocks are associated with Upper Carboniferous tions of sedimentary origin in Brittany, Scotland, some parts of nd (Cornwall), and Scandinavia (near Christiana).

e extrusion of these igneous rocks seems to have been an accom- ent of the crustal disturbances which were in progress during eriod. In middle and western Europe, these disturbances began e close of the Early Carboniferous, as already noted (p. 516), and ued through the Permian. The truncated remnants of the western part (Ireland to central France) of the central European Paleozoic Alps formed at this time, have been called the Armorican mountains,[1] while the eastern part (southern France to northern Bohemia and perhaps beyond), has been called the Variscan Alps. Some of the stubs of these old mountains have been uplifted (relatively) in later times.

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[1] Ramsay, Quar. Jour. Geol. Soc., 1855, p. 185.

[2] Geikie, Text-book of Geology, 4th ed. p. 1047.

The Carboniferous rocks of some parts of Europe have been much deformed. In Mons (Belgium) a shaft 1050 feet deep passes through the same bed of coal six times. At Liége in Belgium, and in the Boulonnais (France), workable coal has been reached after penetrating the inverted Devonian beds.[2] While these are extreme cases, deformation of a less pronounced type is widespread in western Europe, and not unknown elsewhere. Figs. 273 and 204 represent the complicated structure of the system at the localities indicated, and Fig. 274 shows the remarkable subdivisions or branchings of a thick coal-bed.

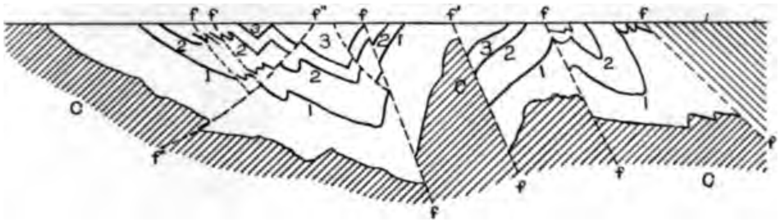

FIG. 273.—Sketch of the Liége coal basin. *D*=Devonian; *C*=Carboniferous; 1, 2, 3=beds of coal; *f*, *f*, etc.=faults. (Vancherpenzeel-Thim.)

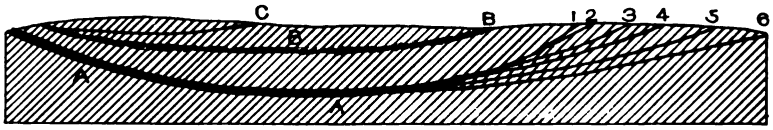

FIG. 274.—Vertical section showing the general disposition and branching of beds of coal (heavy lines) at Commentry. (Fayol.)

Other Continents.

Asia.—The Upper Carboniferous of Asia is represented by both marine and non-marine formations. The latter are often rich in coal. The marine phase is found in eastern Turkestan, at the mouth

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[1] Suess, Antlitz der Erde, Vol. II, 1888, p. 42.

[2] Geikie, op. cit., p. 1053.

e Lena, in some of the mountains of Siberia, in western and north-
rn China, at Vladivostock, in eastern Japan, in Kiangsi in souther
,[1] and in Sumatra. The non-marine phase is found in Heracle
ia Minor, and on the east side of the Middle Urals, where it con-
salt and gypsum, and in various parts of China.

China,[2] three general divisions of the Carboniferous have bee
nized. The lowest corresponds, in a general way at least, wit
ower division of the Carboniferous limestone of Europe (Mississip-
of America); the second is the coal-bearing division, containin
bituminous and anthracite coal; while the third is marine
sting of the usual phases of sedimentary rocks, and seeming t
spond with the Upper Carboniferous limestone of Russia an
ern Europe, and with part of the Carboniferous limestone o
rn North America. The Carboniferous of some parts of China
ially in the province of Shansi, is said to contain coal-beds whic
ss any found elsewhere in the whole world. In the province o
si there is said to be a coal-field, 35,000 square kilometers in extent
the horizontal beds of anthracite reach a thickness of 10 meters
e southwestern part of China there are also great beds of bitu-
us coal.[3] The Carboniferous system is also present in India.[4]

rica.[5]—The Carboniferous formations of northern Africa corre-
l in a general way with those of southern Europe. They ar
ally of marine origin, so far as now known, and without coal
utheastern Africa, a single Carboniferous coal basin has bee
ted near Teté in Zambesi.[6] Upper Carboniferous rocks are als
ted from parts of Sahara and Egypt.

stralia and New Zealand.—The Carboniferous (Permo-Carbon
s) system is well developed in eastern Australia and in Queens
Here, as already noted, the Lower Carboniferous consists o
e sedimentary beds, often much disturbed and metamorphosed
associated with igneous rock. Above the Lower Carboniferou
he Upper or Permo-Carboniferous system, which contains coal

ayser, Formationskunde, p. 203.
ichthofen, China.
ayser, Formationskunde, p. 205. Citing Richthofen, China, Vol. II, p. 473.
ldham, Geology of India, 2d ed., 1893.
ayser and Geikie, op. cit.
ayser, Geologische Formationskunde, p. 207.

and which attains the remarkable thickness of something like 11,000 feet. The system is remarkable because of its singular conglomerates, some of which are of glacial origin. These will be referred to again in connection with the Permian.

South and Central America.—In South America, rocks of Late (Upper) Carboniferous age are somewhat widely distributed, though less so than those of the Devonian period. The system has wide distribution in the lower part of the basin of the Amazon, where it rests on older formations unconformably, and is not generally coal-bearing. In Central America, the same system is reported from Guatemala.

THE LIFE OF THE PENNSYLVANIAN PERIOD.

I. THE PLANT LIFE.

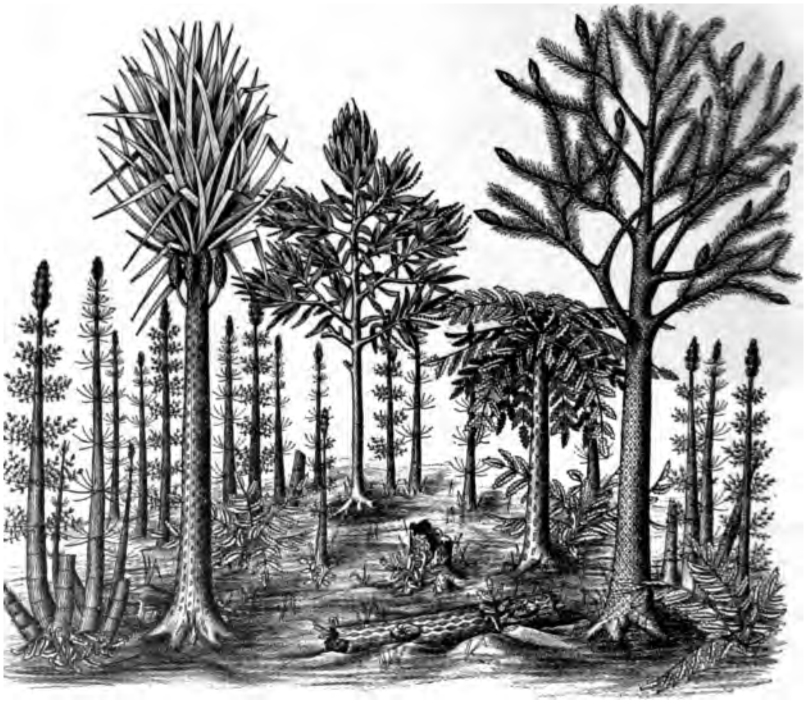
With the opening of the Carboniferous period the supreme biological interest shifted from the sea to the land, and centered in the vegetation and in the amphibians, the forerunners of the great line of terrestrial vertebrates. The leading interest lay in the Coal flora, and to that we turn at once.

The Coal Flora.

The Carboniferous vegetation was climacteric in two senses, which combine to make it doubly interesting; it was climacteric in its preservation, and it constituted a real climax in plant history. The conditions that favored phenomenal preservation have already been set forth. This extraordinary preservation has with little doubt given the Coal flora a degree of prominence over the preceding and succeeding floras that it did not altogether possess, and there is perhaps need to be on guard against over-emphasis; but it was really a great period in the history of plant-life. The leading factor was the pteridophytes which at this time reached their widest deployment, and the summit level of their organization. Ancestral gymnosperms were present, but they held a secondary though not unimportant place. The angiosperms, the present ruling type, had not yet appeared. The lower groups are but feebly represented in the record. It is not certain that there were any mosses or liverworts, though Renault, Zeiller, and others think that mosses were probably present. There are good theoretical grounds for believing that bacteria, fungi, and, in moist

es, semi-terrestrial algæ were present in great abundance, but
obvious reasons their record is obscure. Regnault has identified
eria.

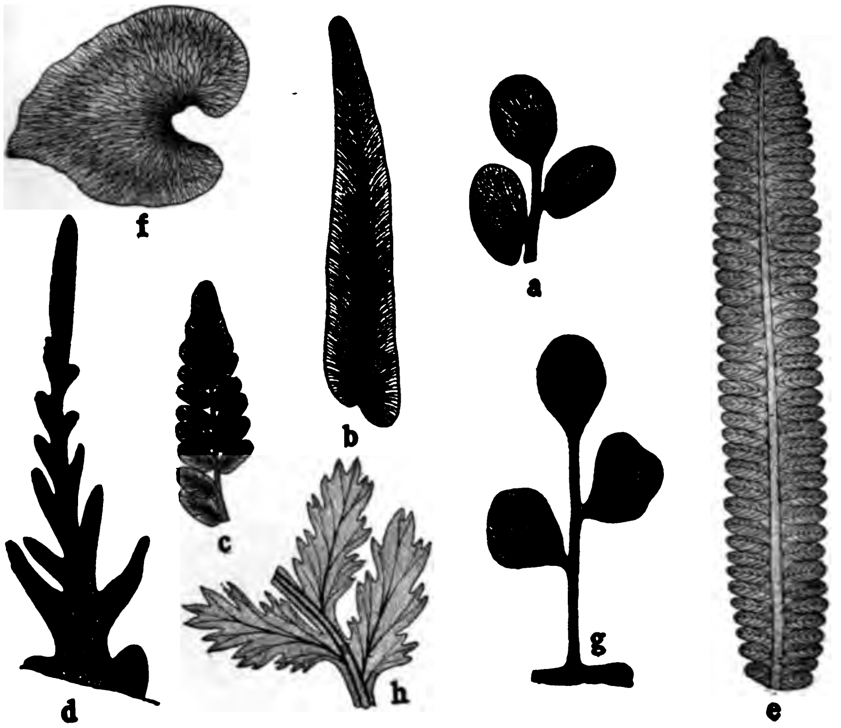
t was emphatically the period of the *Pteridophytes,* and their
oyment in numbers, size and grade of organization was very remark-
. There were true ferns, transitional ferns, and fern-like gym-
erms; there were horsetails in the form of calamarians, spheno-
lls in typical development, and gigantic lycopods in the form
epidodendrons and sigillarias, or, in more technical terms, there



275.—A composite group of leading Carboniferous plants adapted from restora-
ions by various paleobotanists by Mildred Marvin. In the foreground at the
ight, *Lepidodendron;* at the left *Sigillaria;* in the right center rear, a tree fern;
the left center rear, *Cordaites,* at the extreme right and left, *Calamites.*

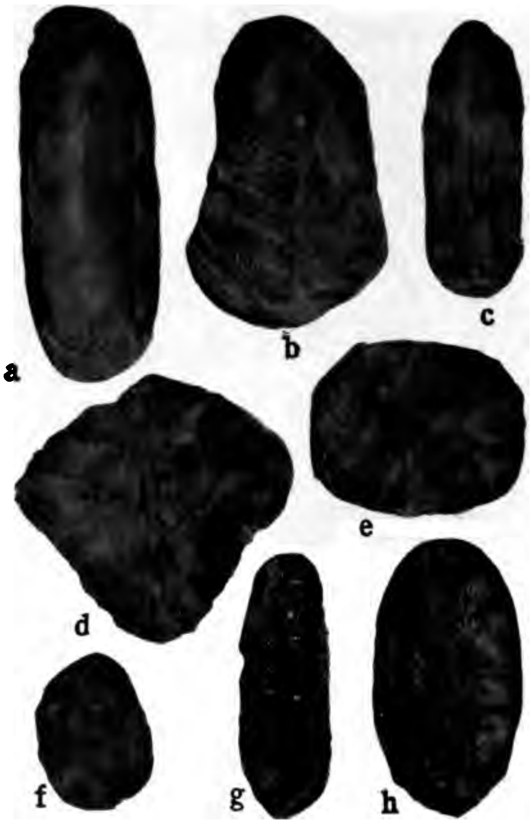
Filicales, Cycadofilices, Equisetales, Sphenophyllales, and *Lyco-*
iales, all the great divisions of the group, and all of these were
ly or quite at their climax, and some of them were verging into
r types. An attempt is made to represent their general aspect
ig. 275.

The Filicales.—Fern-like leaves surpassed all other fossil forms number, but it is now known that many, perhaps even a majority, these belonged to the transition group, *Cycadofilices*. True ferns ere present and apparently abundant, but precisely how abundant yet undetermined. The ferns were a strangely persistent type, like e brachiopods in the sea. At their first appearance in the record, ey had already the distinctive forms of existing ferns (Figs. 275, 276, -*c*, and 277). Later they played a notable part in the floras of any periods, and they are yet an appreciable feature in the plant orld. Ferns may be found to-day that might, so far as outer orm is concerned, be referred to genera prevalent in Carboniferous ime; yet under this general similarity and persistency of form, they ave undergone notable changes of structure and function. In Car-



IG. 276.—A group of fern fronds: *a*, *Neuropteris auriculata*, Brgt.; *b*, *N. angustifolia*, Brgt.; *c*, *N. vermicularis*, Lx.; *d*, *Odontopteris cornuta*, Lx.; *e*, *Pecopteris unita*, Brgt.; *f*, *Dictyopteris rubelia*, Lx.; *g*, *Archæopteris bochsiana*, Goepp.; *h*, *Sphenopteris splendens*, Lx.

ferous times they had more comprehensive characters, and w
art more primitive than now, and in part more advanced, or
more closely allied to the higher type, gymnosperms. The fruiti
ns. however, were only rarely well preserved, and this limits



277.—A group of plant fossils, occurring in concretions in the Coal Measure
azon Creek, Ill.: *a*, *Neuropteris decipiens* Lx.; *b*, and *c*, *Pecopteris unita* B
, *Callipteridium sp.*; *e*, *Annularia longifolia* Brgt.; *f*, *Annularia spenophyllo*
enk., *g*, *Cordianthus sp.*, and *h*, *Lepidostrobus sp.*

ise knowledge of rank and kinship in many species. The majo
herbaceous, but there were many tree ferns some of which reac
hts of sixty feet. One of these is represented in the right rear c
f the group in Fig. 275. The fronds of several prominent gen
illustrated in Fig. 276, some of which, however, probably belon
ransitional types, and not true ferns. The ferns seem to have b

even then about as well differentiated from the horsetails and lycopods as they are now, and so their ancestry is not revealed by close approach to more primitive forms; but, on the other hand, their relations to their descendants seem to be shown by transitional forms, particularly by an interesting group not yet well defined, the *Cycadofilices*, through which they seem to have evolved into cycads, and perhaps into the whole gymnospermous group, though this is an open question.

The Cycadofilices (Pteridospermæ).[1]—It has recently been ascertained that not a few of the fern-like forms possessed structural features which combine the characteristics of ferns and of cycads, and seem to represent the line of evolution from ferns to cycads. They have hence been called *Cycadofilices* by Potonie.[2] It has been further found that some of these bore seeds, and such have been called *Pteridospermæ* by Oliver and Scott.[3] Of these, the best-known form is *Lyginodendron*, illustrated by the excellent restoration of Scott and Allen (Fig. 278), which exhibits the spiny stems and leaves, the highly dissected foliage, the adventitious roots, and the general aspect. The leaves had well-marked palisades (vertically elongated cells arranged side by side as a protection against too intense sunlight, and hence significant of atmospheric conditions), with the breathing pores (*stomata*) on the underside of the leaf. "The whole structure is altogether comparable to that of a fairly coriaceous fern-leaflet at the present day, and indicates that the conditions to which the structure was adapted could not have been fundamentally different from those which prevail in our own epoch."[4] The limits of the group are not yet known, but it is thought to include *Lyginodendron, Heterangium, Megaloxylon, Cladodoxylon, Calamopitys, Medullosa*, and other genera founded on stem-structure, and some at least of the species referred to *Sphenopteris, Alethopteris, Neuropteris, Odontopteris, Callipteris, Linopteris, Aneimites (Adiantes), Callipteridium*, and *Lesleya*, genera founded on fronds.

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[1] Scott, Studies in Fossil Botany, Lectures X and XI, and Pres. Add. Roy. Misc. Soc., Apr. 1895, Pt. 2, pp. 137–140. Also David White, Fossil Plants of the Group Cycadofilices, Smithson. Misc. Coll., Vol. 47, Pt. 3, pp. 377, 390, 1905.

[2] Potonie, Lehrbuch die Pflanzenpaleontologie, p. 60, 1899.

[3] Proc. Roy. Soc., Vol. LXXI, 1903, p. 477, and Vol. LXXIII, 1904, p. 4; Phil. Trans., Vol. 697, B, 1904, p. 193. As the bearing of seed places these forms among the gymnosperms in the most extended sense of that term, it is doubtful whether the term *Pteridospermæ* can properly be retained, and the earlier term *Cycadofilices* is given precedence here.

[4] Scott, Studies in Fossil Botany, p. 326.

frond-genera belong in large part to the stem-genera, the fronds
he *Lyginodendron* being sphenopterids, those of *Medullosa*, neurop-
ls and alethopterids, and so forth; but the full association of fronds
stems has not yet been determined. How nearly the group grades
the true ferns is not known, but in a general way it constitutes a
sition series between the ferns and cycads, and is apparently an
tration of a radical evolution in progress. Initial forms have
identified from the Devonian and Subcarboniferous, and a few

278.—A typical Cycadofilices, *Lyginodendron oldhamia*. (Restoration by D. H. Scott and J. Allen.)

found in the Permian; but the group is essentially Carboniferous,
ch suggests that probably the evolution was mainly accomplished
ween the Devonian and the close of the Carboniferous.

The Equisetales (calamites, horsetails).—What is now the lowly
e of horsetails with a single genus, *Equisetum*, constituted a marked
ure in the Carboniferous flora, in the form of *Calamites*. These
marians not only attained much greater sizes, but much higher
more varied organizations than the present equiseta. Even the
est tropical members of to-day, on the eastern slope of the

Andes, have but slender stems 30 or 40 feet long, whereas the Carboniferous calamites reached a foot or two in diameter and probably 60 to 90 feet in height. The calamarians had hollow stems, or a core of pith only, and casts of the interior are among the most common forms of the fossil (Fig. 279, *a*). The constriction at the node in the cast is due to the internal thickening of the walls, the complement of a ring-like expansion externally. The greatest divergence of the stem from the modern forms consisted in a secondary growth, apparently a means of strengthening the stem to meet the exigencies of great growth. The arrangement of the stem tissues was also much more complex than in modern forms. More notable geologically than either of these features was a great development of cork on the outside, sometimes reaching a thickness of two inches or more. This probably implies adaptation to some climatic or other physical condition. Calamite stems have been found showing wounds which had been healed over by wound cork, as in modern times. The branches from the main trunk were comparatively few, and placed in whorls. The leaves also were placed in whorls (Fig. 279, *b*) and were apparently very much bedwarfed from some ancestral form, but not so much so as in the modern type in which the leaves have almost disappeared. In the Devonian *Archeocalamites*, the leaves were forked; in the Carboniferous calamites, they were lanceolate, implying a progressive simplification of the leaf. The upper and lower sides of the leaves were strongly contrasted, the stomata deeply set, and the palisades radially arranged; in short, the structure was of the type adapted to dry weather (xerophytic) as in the pine and in many desert plants, and also, strangely

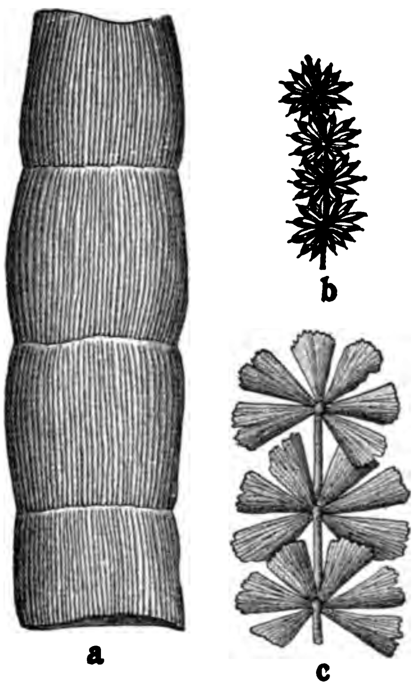

Fig. 279.—Carboniferous Equisetales and Sphenophyllales: *a*, *Calamites cistii*; *b*, *Annularia sphenophylloides*; *c*, *Sphenophyllum longifolium*.

gh, in undrained swamp plants. The trunks arose from sto
rground rhizomes. The root structure was of the type common
l under water or in wet mud. The reproductive organs were
s or strobiles, and gave evidence of higher development than no
calamites were probably associated in thickets or jungles of tl
·brake or bamboo type. Grand'Eury reports great forests of the
tu in central France. They probably frequented swamps ar
nds. As the calamites were well differentiated in the Devonia
history may run far back. Their derivation is uncertain, bı
ıext group throws much light on their relations.

he Sphenophyllales.—Recent studies have shown that the grac
slender plants with whorled leaves, referred to the genus *Sphen*
um (Fig. 279, *c*), and formerly classed as calamites, differ in impc
features from all calamarians, and from the other great divisio
ıe pteridophytes, and form a class by themselves. Their impoı
lies chiefly in the fact that while they have certain calamari
ıres, they have others possessed by the lycopods, which is int
d to mean that these two groups were united with the *Spher*
ales in a common ancestral form.[1] The stems were long, slend
apparently weak, and so a climbing habit has been inferred. T
s were without palisades, suggestive of a shady habitat, perha
of undergrowth. The class was represented in the Devoni
its climax in the middle Coal Measures, and continued into t
ıian and possibly later.

he Lycopodiales.—This was the master group of the Coal floı
tituting trees of large size and attaining to the highest orga
n reached by the pteridophytes. From that high estate, th
since fallen to prostrate or weakly ascending plants of mo
aspect (club mosses, ground pines). The chief genera were *Le*
dron and *Sigillaria*, of which the former was the earlier and si
type. Both take their names from the leaf-scars or leaf-cushic
dos=scale, sigilla=seal) which the trunks retained with mu
stency, implying little or no exfoliation, though the trunks w
ted by secondary growth. The scars are for the most part t
bases or leaf-cushions, rather than the actual scar, which occup
a small part of the cushion. In the lepidodendrons they are
ed spirally (Fig. 280); in the sigillarians, vertically (Fig. 281).

Seward, Fossil Plants, p. 413. Scott, Studies in Fossil Botany, p. 494.

The trunks of lepidodendrons were erect and branched dichotomously at a great height, some having been found 100 feet in length, which is probably not the maximum. The leaves were linear or needle-shaped, ranging up to six or seven inches in length, and were set densely on the branches. The breathing pores were confined to the walls of two very deep furrows on the underside of the leaves. Besides a protecting epidermis, there were thick-walled cells within, as in the modern pine, and the mesophyll was loose without palisades, facts of interest as bearing on climatic or other conditions to be discussed later. The manner of reproduction is a point of peculiar interest, for in some cases the fruit seems to have taken on the characteristics of seeds rather than spores, making the development of the lycopods fall into analogy with that of the fern group, in passing from the spore-bearing to the seed-bearing habit. It is not yet known whether any of these seed-bearing lycopods developed into permanent gymnospermous types or not. One form of the fruit was distinctly winged, and other forms showed adaptation to transportation by wind. Over 100 species have been described.

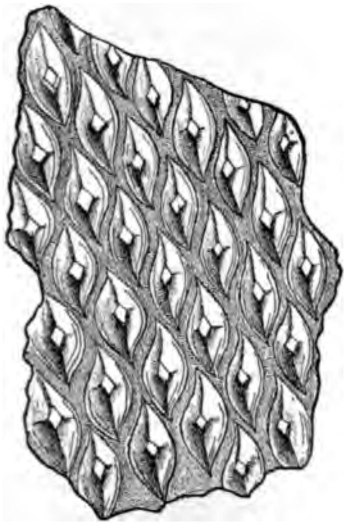

FIG. 280.—Leaf markings of a lepidodendron, *Lycopodites welthermianum*, St.

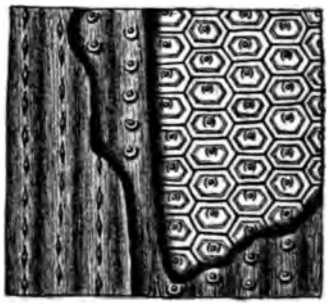

FIG. 281.—Leaf markings of a sigillarian.

The sigillarians differed from the lepidodendrons in being almost entirely unbranched. They were perhaps the largest of the Carbon-us trees, their ribbed trunks being known to reach six feet i ıeter, and 100 feet or more in height. As in lepidodendrons, th s were densely clothed with erect, rigid, linear leaves, which ha deep furrows on the under side to which the breathing pores wei ned. The pores were protected still further by hairs in the fu . The sigillarians, like the lepidodendrons, have secondary woo a thick cork layer. The degree of development of cork is almo ualled in modern trees, except in the cork-oak and its allies.

tigmaria were the roots, or perhaps stolons, of sigillarians an ably of lepidodendrons, the scars that mark them being the poin :tachment of appendages or rootlets. Tap roots are never pre the main roots, usually four in number at the start, spreadin ıontally.

/e have entered thus into detail respecting these remarkab :s, partly because of the interest which they have as the co ents of the first-known great forests, and partly because not ɔf their features are suggestive of the climatic and other physic itions by which they were surrounded, a question to be considere ːntly.

'he lepidodendrons seem to have reached their climax early in tl Measure period and to have declined during the later portio ıat they had nearly all disappeared by the close of the perio ıe latter part of the period, the sigillarians passed the lepidode s in abundance, but they also were decidedly on the wane lose. Whether or not this rather sudden decline, followed by · extinction, was connected with such climatic changes as a ated by the glaciation of India, Australia, and South Afric which seem to have occu ed not far from this time, is a questic h naturally arises, but it cannot be answered demonstrative resent.

he Cordaites.—This was a remarkable extinct family of the gymn nous type, having alliances with the cycads, conifers, and ginkgo yet many distinctive features of its own. The cordaites wei rather slender trees, reaching two or more feet in diameter, an ɔet or more in height. The wood was of the coniferous typ red, as in so many other plants of the period, by a thick con bark. The trunks had a large pith. The leaves were parall ɔd, suggestive of monocotyls of the yucca type, and sometim attained a length of six feet and a width of half a foot. They were preserved in great abundance and make up a large part of some beds of coal. The leaf-structure combined characters now possessed by certain conifers, with others possessed by certain cycads. Palisades were sometimes well developed, though sometimes replaced by water-storage tissues. In one form observed, the leaf had a distinctly fleshy character, as if adapted to xerophytic life.[1] The floral organs were peculiar to the family and have been worked out with marvelous success, even the structure of the pollen having been determined. The inflorescence took the form of separate male and female catkins, arranged on slender stalks attached to the stem between the leaves. The seeds (*Cardiocarpus*) were of the cycadian rather than of the conifer type, and were very abundant and sometimes winged, with a view to wind transportation. In the working out of the structure of the cordaites, it has been shown that many fossils referred, on account of the wood structure, to conifers (e.g. *Dadoxylon*, *Araucarioxylon*), are cordaitean, and that the forms known as *Artisia* or *Sternbergia* are casts of the pith-cavity of cordaites; and not a few other misinterpretations have been corrected.

The transfer of so many supposed conifers to the cordaites leaves it doubtful whether any true conifers are recorded from the Carboniferous, though they were probably represented in the Permian. Numerous seeds are found in Carboniferous beds that cannot certainly be referred to cordaites or other known forms, some of which may belong to conifers. As previously remarked, the upland vegetation is not known, and it is not impossible that conifers, a type specially suited to an upland habitat, prevailed there.

Cycads have been commonly reported from the Carboniferous, but the evidence remains inconclusive; the same may be said of the ginkgos. There is no evidence whatever of angiosperms.

The Distribution of the Carboniferous Flora.

The Coal flora of North America and that of Europe were strikingly similar, implying close geographic relations and like conditions. Nearly all the genera, and about one third of the species, were identical. In part at least, this flora extended to high latitudes in the environs of

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[1] Scott, Studies in Fossil Botany, p. 425.

orth Atlantic, as shown by Heer,[1] and others. Species of *Astro-*
tes, Sphenopteris, Sphenophyllum, Lepidodendron, Stigmaria, and
ites have been found in Spitzbergen, including the cosmopolitan
s *Lepidodendron sternbergii* and *Cordaites borassifolius. Sphenop-*
is reported from Melville Island in association with coal. A
similar flora is found in the Coal Deposits of China, embracing
teridium, Neuropteris, Palæopteris, Sphenopteris, Calamites, Spheno-
m, Lepidodendron, and *Cordaites.* In southern Asia neither the
l nor its bearing is altogether clear. In the Salt Range in
western India, the marine "Productus beds" contain some species
led as Carboniferous, commingled with others of more recent
t, while at its base are bowlder beds with glacial markings, imply-
onditions quite at variance with the warmth and uniformity
y postulated for the Coal Measures period. In the center of the
sula of India, the Talchir formation contains both coal and gla-
eds, and is referred by authors with hesitation to the Upper Car-
rous and Permian. In Australia, the earliest coal-beds contain
odendron and *Cordaites,* but the chief coal-beds contain *Glossop-*
(a tongue-shaped fern) and its associates, to be described later.
y associated with these coal-beds are glacial beds also to be
bed later. The *Glossopteris* flora characterizes all the plant-
hat are later than the glacial beds. Species of *Glossopteris* seem
ve appeared before the formation of the glacial beds, and per-
as early as the Lower Carboniferous. In South Africa there
eds containing *Lepidodendron* and other Carboniferous species,
in unconformably by the Dwyka Conglomerate, a part of which
cial, and above which the *Glossopteris* flora prevails.
king the phenomena of India, Australia, and South Africa
er, they make a puzzling combination. If the chief coal-beds
erred to the Carboniferous proper, it introduces glacial beds,
great floral break, into the midst of a system which has usually
held to be marked by great uniformity the world over. It is,
er, more probable that the glacial beds and all the formations
them are to be referred to the Permian period, and this inter-
ion will be followed in this work. Even when these extraordinary
tions are eliminated, it is not wholly clear that the flora of the
rn regions was very closely identical with that of the northern.

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[1] Flora Fossilis Arctica, IV, 1877.

Lepidodendron and *Sigillaria* extended to that region, but *Glossopteris*, singularly related to the glacial formations, seems to have been contemporaneous with them, while it did not reach Europe till the late Permian and is not known to have reached North America at all. With the present imperfect data for the southern hemisphere, it is uncertain whether the northern coal flora, as a whole, ever extended to that region, although some of its leading genera certainly did. While recognizing the great uniformity of the Carboniferous vegetation of North America, Europe, and a portion of Asia, it is prudent to hold opinion in reserve relative to the southern hemisphere.

Climatic Implications of the Coal-plants.

While the foregoing facts are fresh in mind, it may be best to inquire what suggestions arise from the characters of the plants relative to the atmospheric conditions under which the Coal flora grew. Two rather antagonistic views relative to these conditions have been held. The older of these views regards the accumulation of the thick deposits of coal as evidence of a very luxuriant growth of vegetation, which in turn has been thought to imply a very warm, moist atmosphere, heavily charged with carbon dioxide. The abundance of tree-ferns and of large equiseta, such as now are found only in tropical countries, has been thought to strongly support this view. The occurrence of coal deposits and of the Coal flora in high latitudes has been appealed to as proof of uniformity of climate. This view was formerly held almost unanimously, and still preponderates. Its grounds seem to be strong. The alternative view which has grown up in recent years postulates less rapidity of growth, less warmth and moisture, and more diversity of atmospheric states, as well as a nearer approach to the present atmospheric constitution, though it accepts a somewhat increased percentage of carbon dioxide, and assumes a milder and more uniform climate than the present. The basis of this view (held in different degrees and phases by different geologists) is found in the following considerations. Great thicknesses of coal do not necessarily imply rapid accumulation, any more than great thicknesses of limestone. Given favorable conditions of preservation, a slow growth will produce the thicknesses realized. At present the accumulation of peat, the nearest analogue of coal formation, indeed the first step in coal formation, is most favored in cool climates, and

·fly taking place in high latitudes, though it is also taking place ·ored situations in low latitudes. These situations, however, ther rare and local, while peat formation in high latitudes covers areas. A high temperature, while it promotes a luxuriant growth ·etation, also promotes, in an even higher degree, decomposition, usual conditions.

e characteristic foliage of a warm, moist atmosphere takes the of broad leaves with a thin epidermis and with many and large ing pores, affording abundant facilities for the transpiration isture. The dominant plants of the Coal flora, notably the char·tic lepidodendrons and sigillarias, have narrow leaves with the ing pores confined to deep furrows on the under side, and even in some cases, protected by hairs, devices that are common when ant must guard itself against too rapid expiration of moisture, s technically known as *xerophytic*. These have been carenoted in the preceding descriptions, because of their possible ·ance. It was also observed that most of the leaves of the forest·vere protected from too great action of the sunlight, by palisade ·n the upper sides of the leaves. It was noted further that of the trees were clothed by unusually thick corky bark, as ı protection from external conditions was needed. It has been ted, indeed, that this bark was succulent, rather than corky, but ıe part best preserved, and, according to Dawson, often makes up part of the coal, because the wood and the foliage more largely ·ed, facts hardly consistent with a succulent nature. The remark·reservation of the leaf scars is interpreted, on the one side, to an extremely rapid growth and quick burial, and on the other o mean a texture very resistant to decomposition, and an atmosunfavorable to decomposition, by reason of dryness or coolness. as a whole, the thickness of the bark, its superior resistance ·omposition, the form of the leaves, presenting small surfaces than expansive ones, with their strong sclerenchymatous tis·heir palisades, and their restricted and protected stomata, give ıounced xerophytic aspect to the overgrowth made up of lepidrons, sigillarias, calamites, and cordaites. It is not equally so he undergrowth, the ferns, and the sphenophylls, but this should expected of shaded plants, unless the aridity was extreme.

e force of the inference from the xerophytic aspect of the overgrowth is much weakened, however, by the fact that the vegetation of undrained swamps and bogs assumes many of these xerophytic features, which, in such cases, obviously become pseudoxerophytic. A satisfactory explanation of this phenomenon has not yet been found, nor has its extent and its limitations, either in respect to the nature and degree of swampiness necessary to produce it, or in respect to the kinds of plants or the parts of plants affected, been so thoroughly worked out as to permit a close application to the problem in hand. It is obvious that to fit the case, marsh or bog conditions must have produced pseudoxerophytic adaptations in the great mass of the tree growth, but not in the ferns and sphenophyllous plants. The effects must apparently also be extended to all plants brought into the depositing basins by drainage, whether these were true swamp plants or not, unless a closer study of the Coal flora shall show that the xerophytic aspect was not assumed by all species of the trees involved. It is clear that a more critical study of the problem on all sides is necessary before a final conclusion can be reached. This will become the more apparent when we bring into consideration, as we must a little later, the extraordinary phenomena of glaciation in low latitudes, alternating with coal deposition, though the flora then involved was not identical with that here considered. It bears, however, on the question whether thick coal-beds necessarily mean rapid growth. It will be found that the coal-beds that lie *between* the glacial beds, attained the usual thicknesses.

The influence of increased carbon dioxide on plant growth.—It has been commonly believed that a moderate increase of carbon dioxide in the air would promote a more luxuriant plant growth, and some experiments seem to confirm this.[1] In recent experiments by Brown and Escombe,[2] on the contrary, where an increase of carbon dioxide to the extent of three or more times the normal amount was used, the growth of the plants employed (angiosperms) was appreciably decreased, the structure was adversely modified, the growth of the internodes was checked, the leaves became smaller, and there were changes of a

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[1] E. C. Tealoresco, Influence de l'Acide Carbonique sur la Forme et la Structure des Plantes. Rev. Gen. de Botanique, Vol. II, 1899.

[2] The Influence of Varying Amounts of Carbon Dioxide in the Air on the Photosynthetic Process of Leaves and on the Mode of Growth of Plants. Proc. Roy. Soc., London, LXX, 1902, p. 379; On the Influence of an Excess of Carbon Dioxide in the Air on the Form and Internal Structure of Plants, ibid., p. 413

eritic nature in the tissues and general aspect of the plant, while
lowering was greatly restricted, and in some cases prevented alto-
er. At the same time it was shown that, temporarily, the photo-
hesis of the carbon dioxide was increased, and that the leaves
engorged with starch. The inference was drawn that the dwarf-
effects were due to a disturbance in the adjustments of the plant.
might perhaps be overcome in time by means of a gradual change,
hat no safe conclusions can be drawn relative to the effects of
riation in the proportion of carbon dioxide brought about by a
ge of geological slowness. It is to be noted, too, that the plants
rimented on were all angiosperms, and may be more subject to
rbance by increased carbon dioxide than the lower groups which
l in Carboniferous times.

he seemingly conflicting import of the preceding considerations
s uncertainty to all inferences, and invites reserve in interpreta-
as well as more critical study in the field and laboratory.

II. THE LAND ANIMALS.

he animal life of the land embraced amphibians, insects, spiders,
ions, and myriapods. The development of the amphibians was
most significant feature, for it was the initiation of the great line
nd vertebrates, the ruling dynasty from that day to this.

he rise of the amphibians.—Tracks attributed to amphibians
r as early as the Devonian. In the Mississippian, there is a similar
rd of a four-footed animal of thirteen-inch stride, believed to have
made by one of the primitive amphibians, but in neither of these
ds have any relics of the animal itself been found in America,
only imperfect fossils in Europe. These are sufficient, however,
airly attest the presence of land vertebrates. The amphibian
s from the Carboniferous beds confirm their earlier presence by
a degree of structural differentiation as to clearly imply a long
cedent existence. The conditions of the Devonian period must
ly have been peculiarly favorable for the evolution of the amphib-
for fish having structures akin to the amphibians, and appar-
susceptible of amphibian development abounded, and there
much shifting of land and water areas, and doubtless much
etition and conflict and forcing of new adaptations, as a

result. The emergencies of shoaling water and shifting drainage must inevitably have called into play such powers of air-breathing as the fishes of the time possessed, as well as such ability as they may have had to use the paired fins in locomotion on the land. The great development of the lung-fishes in the Devonian is perhaps one result of this, and they have been regarded as the possible ancestors of the amphibians. This view is now largely abandoned for anatomical reasons, and some branch or branches of the crossopterygians regarded as the more probable ancestors. The connecting link, however, yet awaits discovery; but evolution from some form of fish as early as the Devonian period, if not earlier, is regarded as extremely probable. Because of the fatal effects of salt water on modern amphibians, and for other reasons discussed in connection with the Devonian fish, there is a presumption that the evolution took place in and from fresh water, not unlikely in the continental interior where fluctuations in drainage and precipitation might well have been greater than on the coast, and hence the scantiness of the transition record. Even in the early Carboniferous the record was poor, and relics of amphibians appear in abundance only in the later Coal Measures. They were then already differentiated into five suborders, *Branchiosauria, Aistopoda, Microsauria, Temnospondyli,* and *Labyrinthodonta.*[1] These were all still rather primitive in structure, but they were quite far from being the real transition forms. They are the most primitive terrestrial vertebrates known at present, and if not really the ancestors of all later land vertebrates, they probably represent their general nature. They all seem to have been low, elongate forms of salamandrine aspect, and are classed as stegocephalians (roofed-head), their heads being well roofed over by the bony plates of the skull. They have also been termed labyrinthodonts, from the intricate infolding of the dentine of the teeth of one of the suborders, but the others do not possess the character.

The *Branchiosauria* were perhaps the most primitive in structure, though they have not been found earlier than some of the more advanced types. They were small and salamander-like in form, with short, stumpy, weak limbs and abbreviated tails. The teeth were simple, hollow cones, not labyrinthine. Forms in all stages of growth been found, showing that gills were possessed in the early stages, they were lost later, and that finally the adult amphibian form assumed, thus establishing fully the amphibian metamorphism. ventral surface was usually protected by small overlapping plates utes, and these sometimes extended to the legs and back. Two a (from Linton, Ohio) have been referred to this suborder, per- with some doubt. Other genera are known from the Permian of mia, Saxony, and France.

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[1] The classification here followed is slightly modified from that of Smith Woodward, Vert. Pal., from whom many of the following facts are drawn.

he *Aistopoda* were snake-like forms whose limbs had been atro- l, which implies that a degenerative development had already ı place. The elongation of their bodies involved a notable multi- tion of the vertebræ, one form having no less than 150. The als, or some of them, were protected by scutes beneath, and were d with small ossicles on the back. Their teeth were simple hollow s without infolding. Two genera (*Phlegethontia* and *Molgophis*) been found in Ohio, one or two in the Carboniferous of Ireland, two in the Lower Permian of Bohemia. One of the Irish genera *ichosoma*) is very closely related to the Ohio forms, and they have been supposed to be identical, a significant fact in view of thei separation and their limited means of dispersion.

he *Microsauria* were like the branchiosaurs in having salaman- forms, and conical teeth with simple or only slightly infolde s. Compared with the other suborders, their vertebræ wer like those of the modern reptiles, their skeletons were more com ly ossified, their skulls contained less cartilage, and their limb longer and stronger. Some of them at least probably ran wit d-like agility, and perhaps climbed readily, since many have bee d in the trunks and stumps of trees, as in the coal-mines of Sout ins, Nova Scotia. A score or more of genera, often imperfectl vn, are referred to this suborder from the Carboniferous rica (Nova Scotia and Ohio), and from the Carboniferous (Irelan 282) and the Lower Permian (Bohemia and Saxony) of Europ y were in some respects highly differentiated, and are regarded b paleontologists as the ancestors of some or all the reptiles.

he true labyrinthodonts were doubtless the largest and mo acteristic amphibians of the period, though yet imperfectly know y take their name from the form of the dentine of their teeth, whic usually intricately infolded, giving to the cross-section a beautif labyrinthine arrangement, as shown in Fig. 283. It will be recalled that the holoptychian fishes had a very similar dental structure. The labyrinthodonts differ from the forms referred to the next suborder in having well ossified, biconcave vertebræ, a specialization known to have been reached early in this period. Moreover, the teeth are much more highly labyrinthine than in the known *Temnospondyli*. These features remove the labyrinthodonts from the direct line of ancestry of some, if not of all, the reptiles. Their skulls reached a maximum length of half a meter or more in the Carboniferous period, and by Triassic times, they had attained a length of at least a meter and a quarter, from which the full length of the animal is inferred to have been four or five meters; but in general, if compared with modern crocodilians, they must be regarded as of only moderate size.

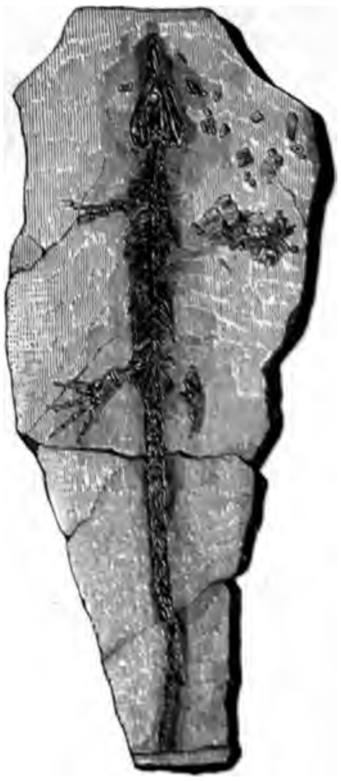
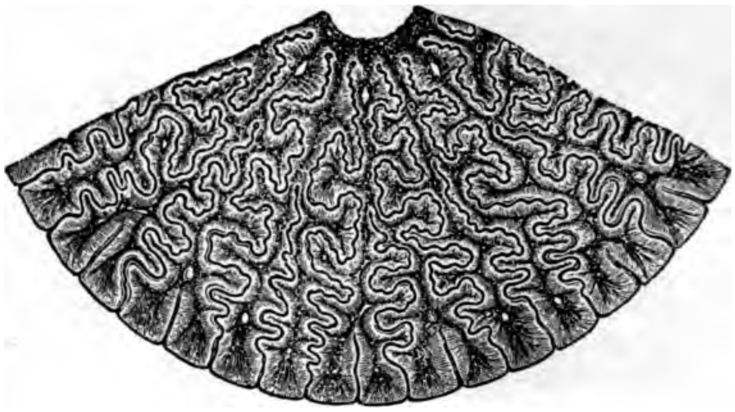


Fig. 282.—Carboniferous amphibian *Lepterpeton dobbsi* Huxley: a microsaurian from Kilkenny, Ireland, about ¾ natural size. (Zittel.)

The *Temnospondyli* differed from the true labyrinthodonts in the divided (rhachitomous) structure of their vertebræ, whence the name. Such vertebræ are thought to have been possessed by the earliest known amphibians from the Lower Carboniferous of Scotland, and forms with similar vertebræ have been found in the upper Carboniferous. The *Temnospondyli* are, however, imperfectly known in the Carboniferous, though they doubtless lived then in abundance and may have made many of the known footprints. They reached their highest development in the Permian, and are supposed by many paleontologists to be the ancestors of all modern reptiles.

Not much is known of the food and life-habits of any of these amphibians. From their teeth, it is inferred that they were predaceous and lived on fish, crustaceans, insects, and other amphibians. At h Joggins, Dawson took thirteen skeletons representing different ibian species from a single sigillarian stump. As such stumps times contained land shells and myriapods, together with amphibkeletons, it has been inferred that such amphibians were climbers, lived on mollusks, myriapods, and similar land life.

n certain places amphibian tracks occur in great abundance, ying that the animals frequented muddy flats; in some places their remains are common; it is therefore inferred that they were dant, at least locally. From their wide differences of structure their considerable specialization, it is inferred that they enjoyed itions favorable both to divergence of type and to development dividual structure, and these should have been found in the new upon which, almost or quite without rivals, they had entered,— mpire of the land.



83.—Cross-section of the tooth of a Labyrinthodont, of later date (Triassic). *stodonsaurus giganteus*, highly magnified, showing the deep intricate infoldings the walls of the tooth. (From Woodward after Owen.)

s the evolution of the amphibians constituted the ascent of the brate type from the water and the beginning of their dominance e land, the event may be well regarded as one of the most signifi- in the earlier history of the earth.

he marked development of insects.[1]—The identification of 400 species of Carboniferous insects from American deposits and a comparable number from the European, previous to 1891, with constant additions since, indicates the great development of this class. They were still, for the most part, of the rather primitive synthetic types, often uniting characters not now found in the same order, and sometimes embracing strange combinations, as a neuropterous wing on an orthopterous body; but advancing differentiation was already manifested. The orthopterous group, embracing cockroaches (Fig. 284, *i*), locusts, crickets, and walking-sticks, were greatly in the lead, followed

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[1] cudder, Bull. No. 71, U. S. Geol. Surv., 1891, and works there referred to. niart, Researches pour servir a l'histoire des Insectes Fossiles des Temps Pris, 1894. Dawson, J. W., Synopsis of the air-breathing animals of the Paleozoic ada up to 1894.

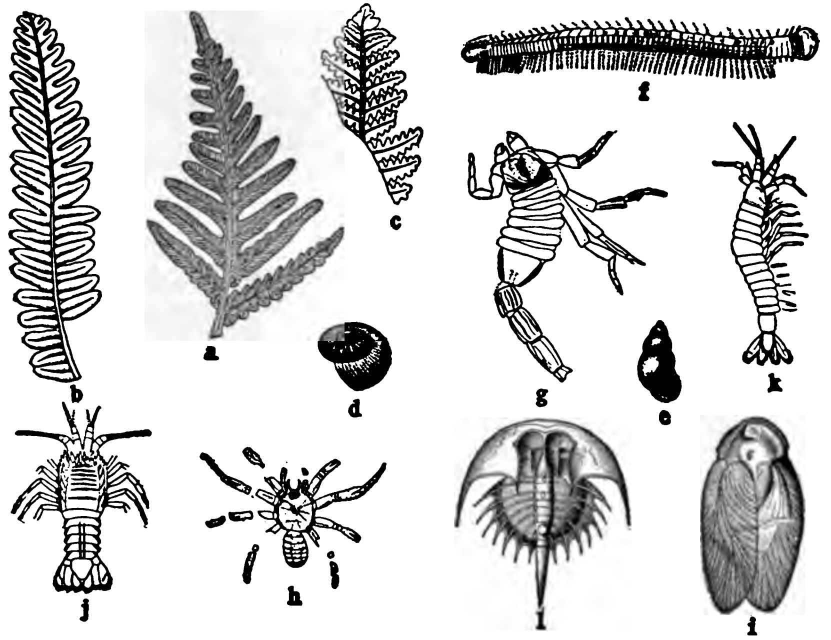

FIG. 284.—CARBONIFEROUS TERRESTRIAL AND FRESH-WATER LIFE. *Plants: a, Callipteridium mansfieldi* Lesq., *b* and *c, Callipteridium membranaceum* Lesq., two species of ferns. *Land shells: d, Zonites priscus* Carp., *e, Pupa vermilionensis* Bradley. These land snails have been referred to genera living at the present time, and although this reference may eventually prove to be incorrect, they are at least close relatives of recent genera. *Insects, etc.: f, Euphoberia armigera* M. and W., a Carboniferous myriapod or thousand-legged worm; *g, Eoscorpius carbonarius*, M and W., a scorpion very similar in type to living forms; *h, Arthrolycosa antiqua* Harger, a spider more primitive than recent forms as seen by the segmentation of the abdomen; *i, Progonoblattina columbiana* Scudd , one of the allies of the modern cockroaches which were the most conspicuous members of the Carboniferous insect fauna. *Crustacea: j, Anthrapalæmon gracilis* M. and W., *k, Palæocaris typus* M. and W., two types of crustaceans found in the Mazon Creek nodules; *l, Prestwichia danæ* M. and W., one of the early allies of the modern horse-shoe crab. (Weller.)

ıe neuropterous group, represented by ancestral mayflies, these ;roups making up perhaps 90 per cent of the whole. *Hemiptera* ;), which had appeared earlier, and possibly *Coleoptera* (beetles) present, but there is no evidence of bees or other *Hymenoptera*, butterflies, moths or other *Lepidoptera*, and no probability of existence, since the flowering vegetation on which they are depend- .ad not yet appeared. There is also no record of flies (*Diptera*). ɔvolution of the class was therefore quite one-sided, and essentially -neuropterous. Curious forms were developed within these s, and rather remarkable dimensions appeared in some cases, ds of wing of a foot or more being reported. The fossilization very irregular, but rather wide-spread, but the species *seem* to be local. This may be due to the probable fact that the different ties where they have been found represent different horizons. s alternative be accepted, it probably implies a rather rapid change ecies, which is not improbable under the extraordinary condi- that surrounded them.

iders, scorpions, and myriopods.—As early as 1890 Scudder eported 75 species of arachnids (Fig. 284, *h*) and 40 species of ›pods (Fig. 284, *f*); scorpions (Fig. 284, *g*) also were present. of the myriopods were vegetable eaters, but one can only wonder all these spiders and scorpions lived on. The record probably not tell the whole story.

ınd snails (Fig. 284, *d* and *e*), in several species, have been iden- .

rom the foregoing it is apparent that the air-breathing com- ty had become somewhat large and diverse, embracing a varied › of amphibians, many insects, spiders, and myriopods, and some ions and snails. It is obvious that all speculative assignments rbon dioxide in the atmosphere must be limited to quantities atible with this life, and the life of flying insects is of a high of activity.

III. The Fresh-water Life.

esides fresh-water plants, the life of the land waters appears ve consisted of certain amphibians (and of all in their early stages), hes, mollusks, crustaceans, probably of the larval forms of certain amphibious insects, and doubtless of many unknown forms. Aside from the developments of the fresh-water fish and of the amphibians, which have already been sufficiently emphasized, perhaps the most suggestive feature was the association of the arthropods with other forms of life. Eurypterids were still in existence, and their relics are so intimately associated with beautifully preserved ferns, calamites, insects, spiders and scorpions as to leave no reasonable doubt that they were true fresh-water forms. In the more notable localities, as at Mazon Creek, Illinois, and Cannelton, Pennsylvania, the fern fronds were preserved with almost perfect fidelity, and without the coiling, crumpling and shredding that would inevitably have attended transportation for any notable distance. At the famous locality on Mazon Creek, uncrumpled fronds form the centers of thousands of concretions (Fig. 277), and insects, spiders, scorpions and eurypterids form the centers of others associated with them. All must have been fossilized with a minimum of transportation, and under the most quiet conditions. Almost equally instructive is the association at Cannelton, shown in Fig. 285, though the vegetation is more fragmentary. A not-distant relative of the eurypterids was present in the beautiful *Prestwichia danæ* (Fig. 284, *l*), whose resemblance to the trilobites on the one hand, and to the king crabs on the other is rather striking, and probably implies a remote ancestral relationship. There were also malacostracans, resembling cray-fish, but referred to a separate order (Fig. 284, *j*), and other crustaceans of shrimp-like appearance (Fig. 284, *k*). Taken together these show a very interesting deployment of the arthropods, and if this be considered in connection with the peculiar association of the eurypterids, ostracoderms, and fishes, of the Devonian and late Silurian, it is not without suggestiveness in connection with the views of Patten (p. 482) relative to the genetic relations of the arthropods and vertebrates, and of Cham-

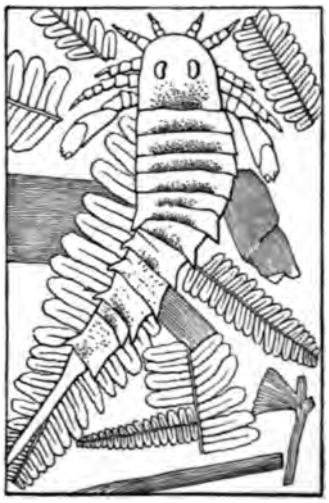

FIG. 285.—Natural association of *Eurypterus mansfieldi* with ferns and calamites. (From Dana after Hall.)

ı relative to the origin of the latter in fresh waters.[1] It will per-
yet appear that fresh water was the environment under which of the most radical of all the biological evolutions took place.
nother phase of association of the fresh-water life of the Car-
erous times is well preserved in a cannel coal deposit at Linton,
[2] This coal is thought to have been formed from fine vegetable
s borne into a fresh-water lake or lagoon, where it settled and
d the relics of the local life, which consisted of more than 20
ɜs of fishes, and nearly 40 species of aquatic amphibians. New-
thought that their individual numbers mounted into the millions.
ıg the fishes were crossopterygians (*Cœlacanthus* and *Rhizodus*),
ɔpterygians (*Eurylepis*), dipnoans (*Ctenodus*) and the peculiar
acanthids (*Orthacanthus*, *Diplodus*, *Compsacanthus*). These last
egarded as elasmobranchs which then, as now, lived in fresh
·, though mainly marine. The amphibians belonged to the sub-
s previously described.

IV. The Marine Life.

ecause of the remarkably close adjustment of the sea-level to
l areas of marshes and flat lands, two phases of sea life had suffi-
prevalence to be worthy of note. The first consisted of those
; that habitually occupied the thin edges of the sea which, in
ɔrm of estuaries, lagoons and shoals, crept in and out on the border
as the relations of land and sea oscillated, while the second
aced the life of the more open seas. This distinction had doubt-
ılways existed, but had not before reached equal importance,
the first phase was not usually well preserved, whereas, in the
regions of this period, it constitutes the better part of the record.
.is phase, where sandy and muddy flats prevailed, the pelecypods
gastropods, with certain of the fishes, predominated, while in
ɑore open seas the brachiopods, cephalopods and the clear-water
more largely predominated.

ıe progress of the fishes.—It is difficult to tell which of the fishes
:l be regarded as marine, which as fresh water, and which as
ıon to salt and fresh water. It seems clear that much the larger
ıer of those found in the American Coal Measures lived in fresh

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[1] Jour. of Geol., Vol. VIII, p. 400.

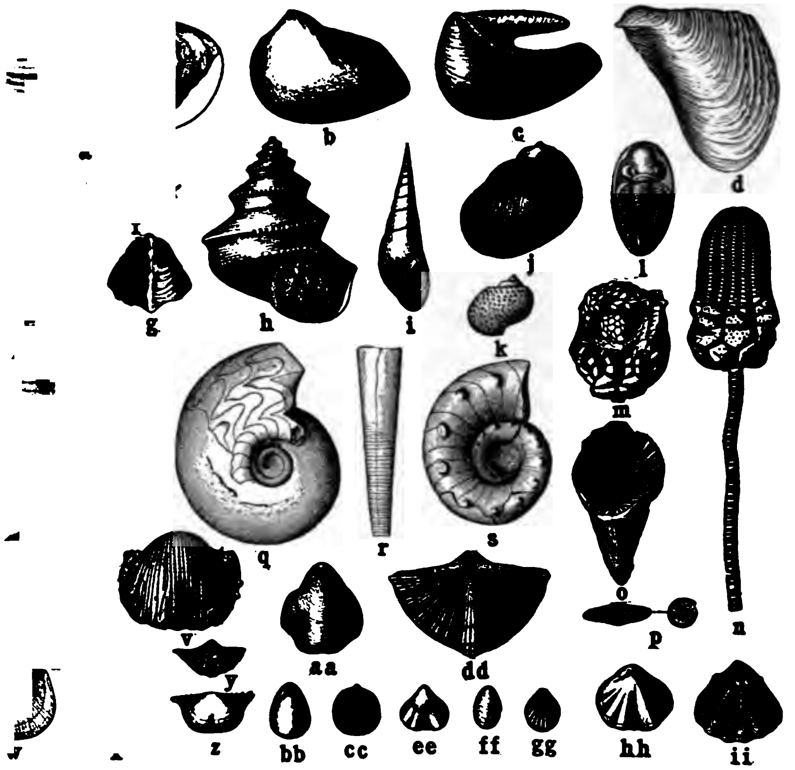
[2] Newberry, Mon. XVI, U. S. Geol. Surv., 1889, p. 211.

water; whether also in salt water is uncertain. It is extremely probable that the sharks armed with shell-crushing teeth (the cochliodonts and psammodonts) were chiefly marine, and that they continued to be abundant through this period, though probably less dominant than in the extensive shell-bearing seas of the Mississippian, while the sharks armed with cutting teeth were also largely marine, but less dominantly so. There was further progress in adaptation to swift movement and in acquiring shapeliness of outline.

Changes in the aspects of the mollusks.—By reference to the pelecypods represented in Fig. 286, *a*, *b*, *c*, *d*, *e*, and *f*, and by comparison with previous figures, it will be noted that this group had assumed an appreciably more modern aspect. They are scarcely Paleozoic in the sense of being very ancient. The period was doubtless very favorable to their advance, by presenting an expansive but shifting and oscillating habitat, that both invited and forced mutational plasticity. The gastropods, on the other hand (Fig. 286, *g*, *h*, *i*, *j*, *k*), show less advance over the earlier types. They resemble those of the Genevieve and even of the Devonian fauna, though quite unlike those of the Osage. On the whole, they still present a distinctly Paleozoic aspect.

Association of lingering and advanced cephalopods.—There was a notable juxtaposition of very ancient and of relatively modern cephalopod types, the former represented by very straight, plain, small orthoceratites (Fig. 286, *r*) that might well belong to the earliest Paleozoic epoch, the latter by closely coiled goniatites (Fig. 286, *q*) with curved sutures that might well be an initial Mesozoic type. The orthoceratites were about to take their departure, the goniatites were about to evolve into the ammonites, the reigning type of the Mesozoic era.

The brachiopods.—As usual the brachiopods held an important place, and their general facies was like that of the Upper Mississippian. *Productus* was the leading form and had many species (Fig. 286, *t*, *u*, and *v*), while *Athyris*, *Chonetes* (Fig. 286, *z*), *Spiriferina* (Fig. 286, *y*), and other genera common in the Mississippian persisted in abundance, but in new species. Spirifers also were again common, some of them exhibiting an advanced state of bifurcation of the plications, as in *Spirifer cameratus* (Fig. 286, *dd*). Some species of the brachiopods were long-lived, and some ranged not only through northern America



86.—THE PENNSYLVANIAN (COAL MEASURES) FAUNA. *Pelecypoda: a, Allorism*
cuneata M. and H., *b, Schizodus wheeleri* Swall., *c, Monopteria longispina* Cox
Myalina recurvirostris, M. and W., *e, Aviculopecten occidentalis* Shum., *f, Avi*
opecten carboniferus Stev.; a group of six pelecypods of types [more or les
nmon in the Pennsylvanian; their relationships for the most part are witl
ms in the Mississippian faunas. *Gastropoda: g, Bellerophon percarinatu*
n., *h, Worthenia tabulata* (Con.), *i, Meekospira peracuta* (M. and W.), *j, Nati*
sis altonensis McCh., *k, Trachydomia wheeleri* (Swall.); a group of gastropod
owing a variety of forms. These Carboniferous members of the class agre
th their ancestors in the entire apertures, the canaliculate aperture so com
n in recent marine gastropods being introduced later. *Trilobita: l, Phillipsi*
jor Shum., almost the last of the trilobites; this genus persists into the Per
an, and then becomes extinct. *Crinoidea: m, Hydreionocrinus acanthoporu*
and W., showing the extravagant development of the ventral sack; *n, Eupachy*
nus magister M. and G., with biserial arms, a type of arm structure introduce
e in the history of the *Inadunata*, but very early in the *Camerata*. This form
proaches some of its Mesozoic relatives, especially such Triassic forms as *Encrinus*
ral: o, Zaphrentis gibsonii White. Corals are rare in this fauna, and are nearl
of the horn-shaped genera. *Protozoa: p, Fusulina secalicus* Say, a littl
aminifer that sometimes constitutes nearly the entire calcareous material o
portant limestone beds. It occurs abundantly in America, Asia, and Europe
phalopoda: q, Paralegoceras newsomi Smith, *r, Orthoceras cribrosum* Gein., *s*
mnocheilus forbesianus (McCh.); three figures representing three types of ceph
pods in the Carboniferous, viz.: (1) the goniatites, with their lobed suture
ich gave rise to the Mesozoic ammonites; (2) the straight orthoceratites whicl

and Eurasia, but into the far Orient and Australasia. Among these wide-ranging species were *Hustedia mormoni* (Fig. 286, *gg*), *Rhipidomella pecosi*, *Enteletes hemiplicata* (Fig. 286 *hh*), *Productus semireticulatus*, *P. cora*, *P. costatus* (Fig. 286, *v*). Some of these, as *P. semireticulatus* and *P. cora*, extended up into the Permian. Other representative brachiopods are illustrated in Fig. 286, *w*, *x*, *aa*, *bb*, *cc*, *ee*, *ff*, and *ii*.

A new phase of the crinoids.—The crinoids were a smaller factor in the fauna than might have been expected from their previous and subsequent history. The cystoids and blastoids seem to have disappeared previously, and no starfishes have been recognized, though they were doubtless present; sea-urchins were rare. The camerate crinoids do not appear, and the inadunate crinoids took the leading place, and celebrated their accession to crinoidal supremacy by developing the ventral sac to unseemly dimensions until it sometimes protruded beyond the arms with balloon-like, or mushroom-like, inflation (Fig. 286, *m*). It is needless to say that these ventral excesses did not last long, and the moral is obvious. Other genera developed in the opposite direction, and lived on becomingly, giving rise, as it would appear, to some of the Mesozoic types. The form *Eupachycrinus magister* (Fig. 286, *n*) is notable as bearing a Mesozoic aspect.

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were nearing the time of their extinction, and (3) the conservative, simple sutured nautiloids which persisted from the Ordovician to the present. In the Carboniferous, the nautiloids were especially characterized by their nodose ornamentation. *Brachiopods: t*, *Productus symmetricus* McCh., *u*, *Productus nebrascensis* Owen, *v*, *Productus costatus* Sow.; the genus *Productus* is one of the most common in the Carboniferous faunas, and these are three of the common species; *w–x*, *Derbyia crassa* (M. and H.), representative of a genus which is the direct descendant of *Orthothetes* of the Devonian and Lower Mississippian; it differs from that genus in the presence of the median septum, seen in *w*; *y*, *Spiriferina kentuckiensis* (Shum.), a common Carboniferous species; the genus *Spiriferina* differs from *Spirifer* in its punctate shell structure. and its median septum; it does not occur below the Mississippian, but extends into the Mesozoic; *z*, *Chonetes granulifera* Owen. This genus occurs from the Silurian to the close of the Paleozoic, and is common from the middle Devonian up; it is characterized by its concavo-convex form, and the spines along the hinge-line; *aa*, *Seminula argentea* (Shep.), a spire-bearing, atheroid shell, one of the commonest Carboniferous species; a near realtive is *S. subquadrata* of the Genevieve fauna (see Fig. 237, *l*); *bb*, *Dielasma bovidens* (Mort.), a common, loop-bearing shell of the Carboniferous; *cc*, *Rhipidomella pecosi* (Marc.), almost the last representative of the orthid shells which were so abundant in the Ordovician (see Fig. 163); *dd*, *Spirifer cameratus* Mort., a very characteristic member of this fauna; *ee*, *Pugnax uta* (Marc.), one of the rhynchonelloid shells; *ff*, *Lingula umbonata* Cox; the Lingulas persisted from the Cambrian to recent time; *gg*, *Hustedia mormoni* (Marc.), a small, plicated, spire-bearing shell; *hh*, *Enteletes hemiplicata* (Hall), a peculiar orthid genus found only in the Carboniferous; *ii*, *Meekella striatocostata* (Cox), a peculiar strophomenoid shell, probably an offshoot from *Derbyia*.

was a close relation between several American and Russian ls, implying intermigration.

nost the last of the trilobites.—The trilobites which commanded remost interest at the opening of the Paleozoic are now almost point of disappearance. The last-known genus is *Phillipsia* 286, *l*), a modest and beautiful form which retains the symmetry ideal type and not a little of its elegance. The extravagances Silurian and Devonian forms had vanished, and the last representive of the family had the chaste beauty of its early ancestry.

her features.—Bryozoans were not uncommon, but the peculiar s for support illustrated in *Archimedes* and *Lyropora* of the pre- period were abandoned. The protozoans were represented by a little foraminiferal shell, *Fusulina secalicus* (Fig. 286, *p*), had about the size and form of a grain of wheat. Their abun- gives character to the "Fusulina beds" which occur in America, e, and Asia. The corals were rare, as might be expected, under vironmental conditions of the time.

already implied, the fauna had many cosmopolitan features, few of its species being common to North America, Europe, and Australia, and its general facies was the same in all these s.

CHAPTER XI.

THE PERMIAN PERIOD.[1]

FORMATIONS AND PHYSICAL HISTORY.

AFTER the formations of the Carboniferous group had reached the development already sketched, a general withdrawal of the sea set in, resulting at length (1) in the exposure of those portions of the central and eastern United States that had been covered by it, at least occasionally, and (2) in the restriction of the submerged area in the western part of the country, an area which had been somewhat generally and constantly covered by the sea during the preceding period. With the beginning of the Permian period, the waters which lay upon the continent were partly in the form of lakes and inland seas, and partly connected with the open ocean. Even the areas which the sea overspread at the beginning of the period were largely abandoned by it before the close. As already noted, the deformative movements which finally resulted in the folding of the Appalachian and Ouachita mountains seem to have been inaugurated at about the close of the Carboniferous period, and these movements were doubtless a main cause of the general withdrawal of the sea. These movements appear to have been more profound than those which shifted the epicontinental seas in the preceding periods.

These movements reflected themselves both in the distribution of the Permian formations and in their character. While fresh-water sedimentation continued much as before in some parts of Pennsylvania, West Virginia,[2] Maryland,[3] and Ohio,[4] giving rise to the "Upper Barren Coal Measures"—a name which suggests the close connection of these formations with those which preceded—the Appalachian belt farther south seems not to have been the scene of deposi-

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[1] The Permian is often regarded as a part of the Carboniferous. For recent advocacy of this view, see Jour. of Geol., Vol. VII, pp. 321–41.

[2] White, West Virginia Geol. Surv., Vol. II, pp. 100–123.

[3] Martin, Maryland Geol. Surv., Garrett County, p. 144; O'Hara, Allegany County, p. 128, and Prosser, Jour. of Geol., Vol. IX, p. 428.

[4] Prosser, Jour. of Geol., Vol. XI, p. 523.

The Upper Barren Measures are commonly separated from ɜnnsylvanian system on the basis of their plant fossils, rather ɔecause of any stratigraphic break at their base.

e Pennsylvania section of the Permian is shown in Fig. 287. ɜr north also, in Nova Scotia, New Brunswick, and Prince rd Island, non-marine Permian strata rest on Carboniferous in ı way as to show that sedimentation was not greatly interrupted, he two groups are separated on the basis of fossils only. The an of Pennsylvania, West Virginia, and the Acadian region to represent only the early part of the period, after which these ıs appear to have been no longer subject to deposition.

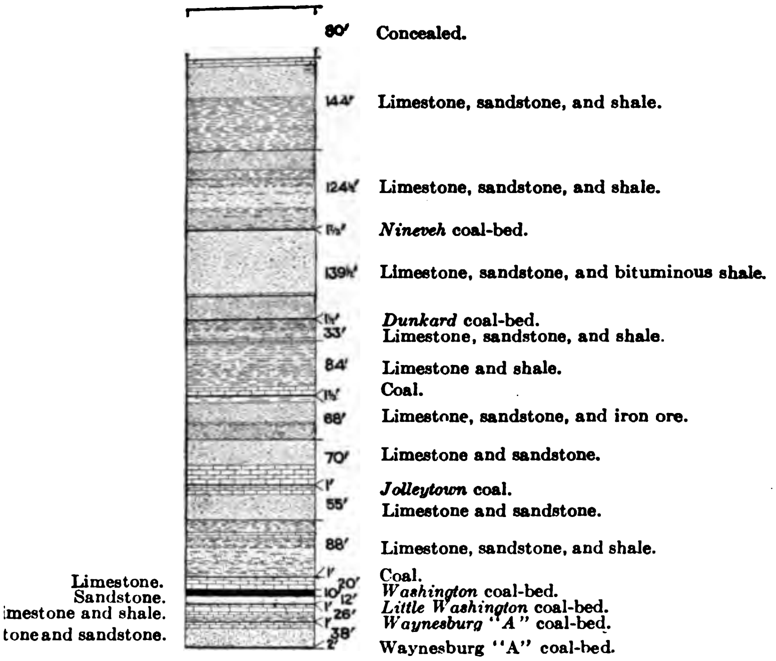

FIG. 287.—Section of Permian in Pennsylvania.

ɾrmian vertebrate fossils (not marine) have been found in what ɾrs to be the channel of a stream eroded in the Coal Measures ɜtern Illinois.[1] Beds thought to be Permian also occur in neighɡ parts of Indiana.[2]

est of the Mississippi, the Permian system has a more extensive

ıse, Jour. Geol., Vol. VIII, pp. 698–729.

latchley and Ashley, 22d Ann. Rept. Indiana Dept. of Geol., etc., p. 22, and 23d ɛept., p. 80.

development, though far less wide-spread than the Pennsylvanian. The Permian strata are best known in Texas, Kansas, and Nebraska, and though the sea was not entirely excluded from this region, it appears, where present, to have been shallow. Locally and temporarily, inland seas were cut off from the ocean. Early in the period the Texan area of sedimentation seems to have been separated from the Kansan by the beginnings of the Ouachita mountains, the uplift of which has been mentioned.

In Kansas[1] and Nebraska[2] the older Permian beds are marine, and though the connection has not been traced, the Permian of these states is probably continued northwestward to Wyoming[3] and South Dakota,[4] for in the Laramie mountains of the former state, and in the Black Hills of the latter, marine Permian beds, with fossils very similar to those of Kansas, are found. The marine Permian of Kansas is overlain by beds containing gypsum and salt, and possessing other features which show that the open sea of the region was succeeded by dissevered remnants, or by salt lakes whose supply of fresh water was exceeded by surface evaporation. Connected with these saline and gypsiferous deposits, and overlying them, are the "Red Beds," sometimes referred to the succeeding Trias; but they appear to be late Permian, in the main at least. This conclusion seems applicable to a large part of the Red Beds east of the mountains, though some are probably Triassic. Some of the Red Beds in western Texas and New Mexico are perhaps later than Permian, and some in Indian Territory and Kansas are possibly the equivalent of portions of the Pennsylvanian system.

The gypsum beds of Iowa may be of Permian age, though there is nothing in their relations to make this certain.[5]

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[1] For an account of the Permian of Kansas see Prosser, Geol. Surv. of Kansas, Vol. II, 1897, pp. 55–97. This article also contains references to the literature concerning the Permian of the western interior. See also papers by the same author on "The Permian and Upper Carboniferous of Southern Kansas," Kans. Univ. Quar., Vol. IV, 1897, p. 149, and on "The Classification of the Upper Paleozoic Rocks of Central Kansas," Jour. Geol., Vol. III, pp. 682–705, and Vol. X, pp. 703–37; Cragin, Permian System of Kansas, Colo. College Studies, Vol. VI, pp. 1–48; Gould, Jour. Geol., Vol. IX, pp. 337–40; and Beede, Am. Geol. Soc., XXVIII, p. 47; and Prosser and Beede, Cottonwood Falls, Kan. folio, U. S. Geol. Surv.

[2] Knight, Jour. Geol., Vol. VII, pp. 357–74, and Barbour, Nebraska Geol. Surv., Vol. I, p. 129.

[3] Knight, Bull. 45, Wyo. Experiment Station, and Jour. Geol., Vol. X, pp. 413–22

[4] Darton, 19th Ann. Rept., U. S. Geol. Surv., Pt. IV.

[5] Wilder, Iowa Geol. Surv., Vol. XII, p. 111.

ıe Kansas section of the Permian is as follows:[1]

Names of Formations.			Thickness in Feet.	Characteristics.
retaceous				
		Unconformity		
Cimarron Series.	Kiger Stage.	Taloga formation.....	25–30	Chiefly maroon-colored shale below, with massive red an grayish-white sandstone above; no fossils.
		Day Creek dolomite...	1–5	Gray to white; no fossils.
		Red Bluff formation..	175–200	Light red sandstone and shale In Oklahoma contains marine invertebrate fossils.
	Salt Fork Stage.	Dog Creek formation..	30 ±	Dull-red, argillaceous shales laminæ of gypsum in lowe part, and ledges of dolomit in the upper; no fossils.
		Cave Creek formation.	50	One massive bed of gypsum, o two such beds separated b red clay-shale; caverns abundant.
		Glass Mountain formation..............	200–225	Fine-grained, bright-red sandstone of varying hardnes below, with highly gypsiferous clays above; no fossils
		Kingfisher formation..	800 ±	Saliferous and gypsiferou prevailingly dull-red o brown shales. Lower par in Oklahoma has vertebrat remains.
Big Blue Series.	Summer Stage.	Wellington shales.....	200–450	Mainly bluish gray to slate colored; occasional beds o dolomite and gypsum.
		Marion formation.....	400	Mainly buff, thin-bedded limestones, and shales; locall contains beds of gypsum an rock salt; lower portio contains marine fossils.
	Chase Stage.	Winfield formation...	20–25	Cherty limestone and shales marine fossils.
		Doyle shales.........	60	Varicolored shales; occasional thin beds of sof limestone; marine fossils.
		Fort Riley limestone..	40 +	Massive and buff to thin bedded and shale; marin fossils.
		Florence flint........	25	Cherty limestone; marine fossils.
		Matfield shales.......	60–70	Varicolored shales with som limestone; marine fossils.
		Wreford limestone....	35–50	Some portions very cherty marine fossils.
ennsylvanian system				

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osser, Jour. of Geol., Vol. X, pp. 703–737; Cragin, Colorado College Studies I.

In Texas and the region south of the Ouachita uplift, the system has its greatest development. In the Staked Plains (Llano Estacado) it attains a thickness of 7000 feet. The oldest formation of the system (the *Wichita*) indicates that the critical attitude which characterized the surface farther east during the Pennsylvanian period, now affected Texas, for the beds are partly of marine and partly of fresh-water origin. These beds are succeeded by a formation of limestone (*Clear Fork*), which indicates a submergence sufficient to allow free entrance of the sea. Advance of the sea is further indicated by the fact that the Middle Permian beds overlap the Lower, and rest upon the Pennsylvanian, where no Lower Permian intervenes. The Upper Permian (*Double Mountain*) which follows indicates a reversal of relations, for much of Texas was again cut off from the ocean and converted into an inland sea, or into inland seas, in which the usual phases of deposition under arid conditions took place. Occasional beds of limestone with marine fossils point to occasional incursions of the sea, while the deposits of salt and gypsum point with equal clearness to its absence, or to restricted connections.[1] In the Guadalupe mountains of western Texas, the Permian system has a thickness of 4000 to 5000 feet, and carries faunas unlike those of other regions of North America, but similar to those of the late Paleozoic of Asia.[2]

The Permian sea which overspread part of Texas was perhaps continuous to the west, for a part of the time, as far as the Basin region (Utah); but if so, the continuity of the beds has since been interrupted by erosion. Fig. 288 shows the manner in which the Permian now occurs in some parts of the plateau region of the west. Beds thought to be Permian are known in New Mexico,[3] in northern Arizona,[4] and at other points in the surrounding territory, and in the Wasatch mountains, but not farther west. Throughout much of the area west of the Rocky mountains, the Permian has not generally been differentiated. If it is present, as it doubtless is in some places, it has been classed either with the Carboniferous below or with the Trias above. There is often perfect conformity between the Carboniferous below and the beds classed as Trias above, suggesting the presence of unsepd Permian between. In northern Arizona, however, and in south- ;rn Colorado,[1] and perhaps at other points, there is an uncon- ty at the base of the Trias.

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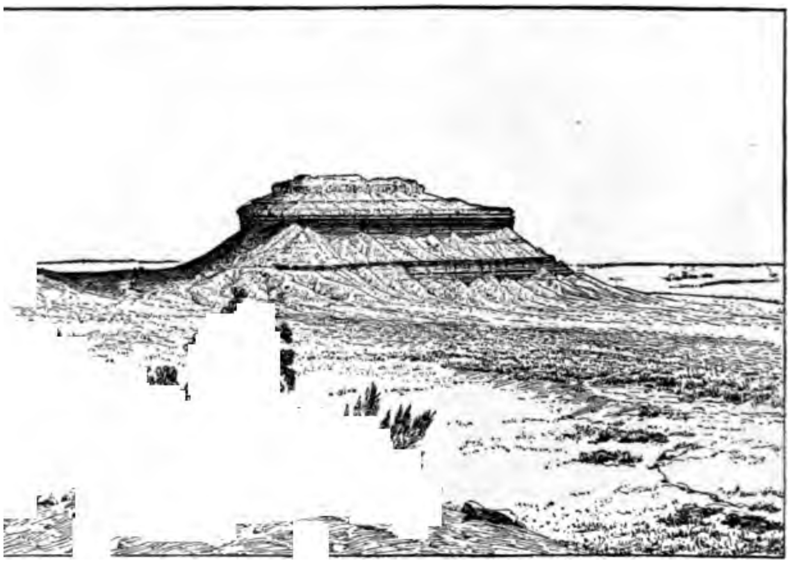
[1] For Permian of Texas, see Cummins, Geol. Surv. of Texas, 2d Ann. Rept., pp. 394–424. Ibid., 4th Ann. Rept., 212-32.

[2] Girty, Am. Jour. Sci., Vol. XIV, 1902, pp. 363–368.

[3] Herrick, Jour. Geol., Vol. VIII, pp. 112-125; and Am. Geol., Vol. XXXI, p. 76.

[4] Walcott, Am. Jour. Sci., Vol. XX, 1880, p. 221.

the beds tentatively referrred to the Permian be really such, show that the relatively continuous and clear seas of the Pennsyl-



88.—A butte composed largely of Permian rock, Northern Arizona (Dutton, U. S. Geol. Surv.

.n period in this region had given place to much shallower and ;ontinuous bodies of water, often of more than normal salinity, that at many points there were interruptions of sedimentation .e close of the Pennsylvanian.

ed Beds, generally classed as Triassic, occur even north of the :d States.[2] Their thickness is not great, and they perhaps belong the Red Beds farther south, most of which are now usually classed ;rmian.[3]

he Permian deposits of the far west, as well as some of those of

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ross, unpublished evidence.

ıawson, Bull. Geol. Soc. Am., Vol. XII, p. 74.

ome of the upper Red Beds of central Wyoming are thought to be Triassic ;ton) on the basis of fossils collected by Knight and Branson. The horizon Triassic fossils is 550 feet above the base of the Red Beds, and 250 feet below ıp.

the longitude of Texas and Kansas, are often highly colored, red being the dominant hue. This color so often characterizes formations known to have been made in inclosed basins, that the connection can hardly be fortuitous.

It is a singular fact, though it may be no more than a coincidence, that certain thin but well-defined layers of clay in the Permian beds of Texas, like certain layers of the Permian in Europe, contain considerable quantities of copper ore. In Europe, however, the copper is confined to a single layer, while in Texas it is distributed through several. This correspondence is perhaps worthy of mention, especially because copper ores are not, on the whole, abundantly distributed, and this is not their usual mode of occurrence.

Thickness.—In the Appalachian region, the Lower Permian beds, sandstone and shale, with thin seams of coal, have a thickness of about 1000 feet. The Upper Permian is wanting. In Kansas the thickness is twice as great, while in Texas it reaches 7000 feet. The Permian system, like the Carboniferous, is thicker in the southern interior than in the Appalachian region.

Correlation.—In the region east of the Mississippi, the Permian is so closely associated with the Coal Measures that the two were formerly classed together. Were this region only considered, this would appear to be the best classification. In the western part of the continent, on the other hand, the differentiation of the Permian from the Carboniferous is more distinct, and its relation with the Trias is generally close. In the Texas-Kansan region, for example, the relations of the Permian to the Trias, if the beds referred to the Trias are really such, are so close as to have caused the frequent reference of the upper part of the former to the latter. Perhaps the Permian period is best looked upon as a transition period from the Carboniferous to the Trias, and so from the Paleozoic to the Mesozoic. According to this view, its close relationship to the underlying system in some places, and to the overlying system in others, is natural.

THE FOREIGN PERMIAN.

Europe.

In Europe, as in America, the Carboniferous period was brought to a close by very considerable changes, for much of the area which een receiving deposits during that period was exposed to ero- at its close. Subsequently, through further changes, much of me surface was again brought into a position for renewed depo- , partly from fresh and partly from salt waters. The Permian n thus formed is on the whole much more distinct from the Car- rous than the Permian of the eastern part of North America, s much better known.

uring this period Europe was divided into two somewhat dis- provinces, a division which began to show itself in the later part Carboniferous period, when the Upper Carboniferous limestone n process of deposition in southern and eastern Europe. Corre- ling in a general way with these two provinces, the Permian wo somewhat different phases known as the *Dyas* and the *Per-* respectively. The former name had its origin in the twofold on of the system, and the latter came from a province of Russia the formation is well developed. In England, both phases e system are represented, the Dyas in the east and the Per- in the west,[1] and in the Baltic province of Russia, the Dyas is found. In general, the Permian system is somewhat more spread than the Upper Carboniferous which it overlies, often formably, and which it overlaps in various directions.

xcept in Russia, where its extent is great, the Permian appears e surface around mountain cores and in narrow strips only; but the positions of these outcrops, it is inferred that the formation, reality widespread beneath younger beds.

wer Permian.—Where the Dyas phase of the formation is developed nerally in western and central Europe, the Lower Permian (*Roth- de)* consists of a series of fragmental beds made up of shale, tone, conglomerate and breccia, with which there is associated ge amount of igneous rock, now in the form of lava-sheets, now e form of dikes, and now in the form of volcanic material. The nt of igneous matter is so great (especially in Scotland, Bavaria, southern France[2]) and is so widely distributed (occurring also gland, the Vosges and Thüringerwald mountains, the Alps, etc.) it is to be looked upon as rather characteristic of the Lower Per-

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[1] Geikie's Text-book of Geology, p. 1070.

[2] Ibid., pp. 1070, 1073, 1075.

The Rothliegende is often unconformable on the Carboniferous. The character of the formations and of their fossils is such as to show that much of the sediment was accumulated in inland seas, and in salt and fresh lakes. Gypsum, salt, and a meagre fauna of dwarfed and stunted species, some of which are of certain marine types,[1] are among the distinctive marks of the series. To these inland areas of sedimentation the sea sometimes had access, as the nature of the formations and their fossils show. It may have had limited access, even while the salt and gypsum beds were being deposited. There were lakes of fresh water also in which sediments gathered, and in these parts of the system, fossils of terrestrial as well as lacustrine life are found. Even in some of the Permian limestones (as in France) fresh-water fossils only are found. The shallow-water or subaërial origin of much of the Permian is shown by the sun-cracks, rain-pittings, ripple-marks, etc. Tracks of terrestrial and amphibious animals, impressed in the muds and sands while they were accumulating, are also found.

In keeping with the conditions of its origin, the Rothliegende often contains beds of coal. This is the case in France, where one coal-bed attains a thickness of 82 feet;[2] in Saxony, in the Harz, Schwarzwald and Thüringerwald mountains; and in Bohemia where the valuable coal-beds occur in the Rothliegende more than in the Carboniferous.[3] In the region of the Ural mountains, too, the Lower Permian beds are non-marine and coal-bearing.[4]

Especial interest attaches to the conglomerates and breccias of the system because of their likeness to glacial drift.[5] This likeness is found not only in the presence of large bowlders, but in their character and in the matrix in which they are set. Furthermore, the stones have now and then been observed (Midlands and west of England) to carry marks which have been thought to be glacial striæ. This origin of the marks, however, has been called into question. The con-

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[1] Kayser, op. cit., p. 226.

[2] Idem, p. 253.

[3] Idem, p. 230–238.

[4] De Lapparent, Traité de Géologie, p. 969.

[5] Ramsay, Q. J. G. S., 1855, p. 185; and Geikie, op. cit., p. 1064. There seems to be some question as to whether these formations should be referred to the Carboniferous or the Permian.

:rate is wide-spread, and in some cases contains bowlders whic been transported considerable distances.

ıe Lower Permian strata of the Dyas phase are often red, ε sted by their German name (*Rothliegende*). Strata of the san onstitute at least a part of the "New Red Sandstone" of Gre in. As a matter of fact, however, while the colors of this form ıre usually striking, other colors than red are often found. Tł that the red color is characteristic of the same system in muc nerica has been noted.

ı contrast with the Rothliegende, the Lower Permian of much ern Europe is of marine origin, and is generally conformable c arboniferous. Non-marine Permian beds are, however, found outh as the Alps, and even into Italy. On account of its fossi ts relations to the Carboniferous, the Lower Permian of southeı pe has been thought to be older than the Rothliegende.[1] It y distributed, occurring in the Alps, Italy, Sicily, the Pyrenne ı the Balkans.

he typical Permian phase of the system underlies the larger pa ıssia (in Europe), and appears at the surface over a large are e southeastern part of that country. It is generally conforn on the underlying Carboniferous. Its lower part is made ly of clastic beds bearing non-marine fossils. Some beds, hov contain the shells of marine species. The Lower Permian exten ova Zemla on the north, and to the steppes of Kirghiz in Asiat ia, on the east.[2]

he Upper Permian.—The Upper Permian of western and centr pe (the *Zechstein* of Germany) is unlike the Lower in sever rtant respects. It contains much more limestone and dolomit ıeither coal, igneous rock, nor, except at its very base, conglome Such characteristic marine fossils as cephalopods and cora enerally absent,[3] and from the stunted aspect of the fossils, aı the association of the dolomite with gypsum, salt, etc., it ght that the limestone and dolomite may be largely chemic pitates. Some parts of the Upper Permian are, however, of mariı origin. In southern Germany, Bohemia, and France, the Zechstein has little representation.[1]

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[1] De Lapparent, Traité de Géologie, p. 985.

[2] Kayser, op. cit., pp. 253–255.

[3] Idem, p. 226.

The Upper Permian of western Europe is remarkable for the fact that certain thin beds of peculiar character are exceptionally persistent over wide areas. Thus at its very base, there is a thin but persistent bed of conglomerate (perhaps a basal conglomerate), and a little higher in the series there is a thin layer, rarely reaching a thickness of as much as five meters, and often less than one, which, over very considerable areas, carries abundant ores of various metals, among which copper is prominent. It also carries abundant fish remains, and is rich in bitumen. This layer (*Kupferschiefer*), thin as it is, has long been worked in Germany, now chiefly about Mansfield, especially for the copper. The ore occurs in small grains, distributed through the sedimentary bed. The grade of the ore is rather low, but it is

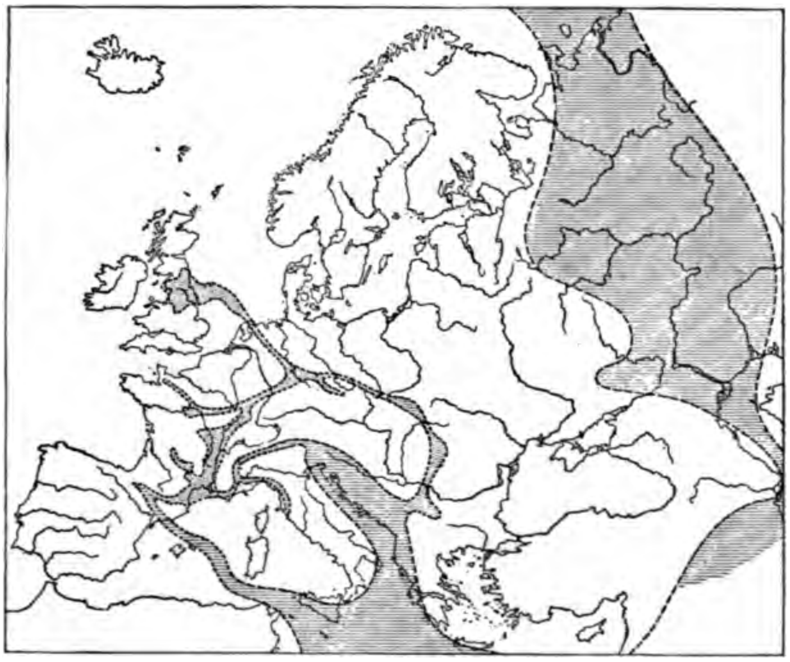

FIG. 289.—Sketch map of Europe showing the areas of deposition in the early part of the Permian period. The lines indicate areas of marine sedimentation, and the dots areas of non-marine sedimentation. (After De Lapparent.)

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[1] Kayser, op. cit., p. 225.

worked. The origin of the copper has been referred to sul
ıe mineral springs, which have even been supposed to have poisone
raters and so to have destroyed the organisms in them, the deca
ıose remains gave rise to precipitating agents. More in the natur
of things, the ore has been referred to the leaching of igneoı
other rocks by surface-waters tributary to the basin in whic
leposit took place, the precipitation of the ore being assigned t
ırganic agencies common to inhabited waters. Such an explan
gains in plausibility from the fact that the area where the copp
's appears to have been a somewhat enclosed basin, rather tha
ıpen sea. The ores are best developed in the vicinity of fault
ı indicates that they are, in part at least, of secondary origi
singular fact that the Permian of Texas, as well as that of Europ
ıins copper ores in similar relations, has been referred to.

he Upper Permian of central and western Europe contains tl
est salt-beds known in any part of the earth. Near Berlin, oı
ese salt-beds has been penetrated to the depth of about 4000 fee
its bottom has not been reached. In addition to common sal
of potash and magnesium were locally (Stassfurt) deposited i
quantity as to be commercially valuable. The world's suppl
ıtassium salts, with the exception of saltpetre, comes from thes
[1] Like the rock salt, these salts probably represent precipitat
the waters of inclosed basins under special conditions.

he Upper Permian of eastern Europe is largely of non-marir
ı, as shown by the salt, gypsum, etc., which it contains. Marir
s are, however, not wanting,—are indeed rather more commc
in the Zechstein farther west. Over wide areas, the beds a
gnated with copper. The flora is of a type (*Glossopteris*) n
developed elsewhere in Europe, but prevalent in the Permian
o-Carboniferous of Africa and Australia.[2].

he Permian system is present in Spitzbergen, where it is whol
ıe. The fossils are more closely allied to those of the north Paci
to those of Russia and India, as if there were a boreal mari
nce.[3]

eneral.—On the whole, the Permian system of Europe possess features which show that the general attitude of the continent was comparable to that of North America at the same time. In both continents there are beds which accumulated in fresh water; in both, beds which were laid down in salt lakes or inland seas; and in both, beds deposited on the floor of epicontinental seas. Great areas in both continents seem to have maintained a halting attitude near the critical level during much of the period, while in both continents there were considerable areas of dry land.

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[1] Kayser, Geologische Formationskunde, p. 250.

[2] Amalitzky, Review of article by, Geol. Mag., 1901, p. 231

[3] De Lapparent, p. 986.

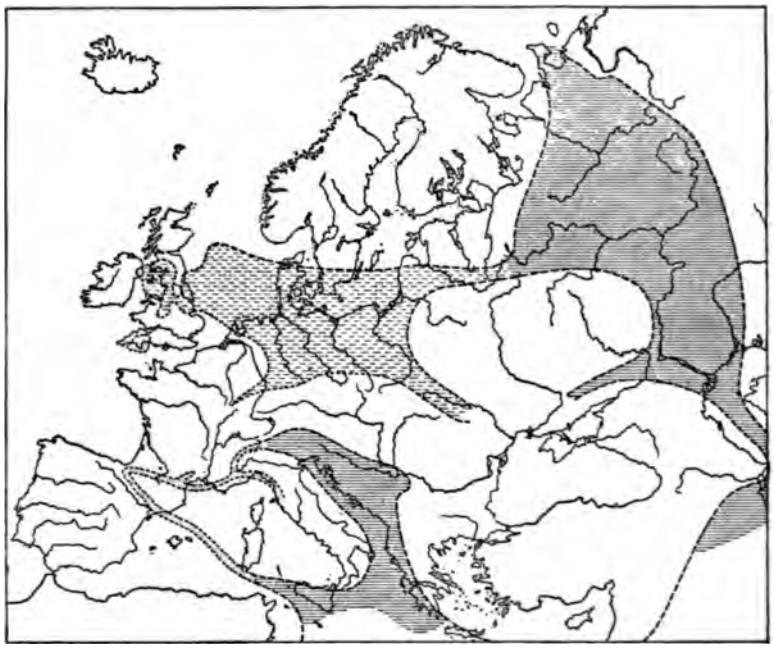

FIG. 290.—Sketch map of Europe during the later part of the Permian period. The lines indicate areas of marine deposition, the broken lines areas of lagoon deposits; and the dots, areas of continental (land) deposition. (After De Lapparent.)

The differences between the continents are not less instructive than the likenesses. The Permian period was distinguished in Europe by great igneous activity, while that of America, though marked by the growth of mountains, was essentially non-igneous. The Permian system of Europe seems to be more closely allied, stratigraphically, with the Trias than with the Carboniferous, and while the same is true of the western part of North America, the opposite is true for the eastern part.

other parts of the world the Permian is widely developed. I ries about the Indian Ocean, including South Asia, Australia southern Africa, there is usually a less distinct break betwee arboniferous and the Triassic systems than in Europe, and, locall ist, the Permian seems to completely bridge the interval.

ustralia.—In South Australia, above a series of Coal Measure lants of which are of the normal Carboniferous types, there i es of marine beds alternating with beds which contain land plant e those of the Coal Measures below. Considerable beds of coa lso included in the series. Interstratified with these marin and coal seams there are considerable beds of conglomerat stinctive glacial type (Fig. 291). Some of the bowlders of th omerate are striated in such a way as to leave no doubt as t glacier origin. Furthermore, the substratum on which th ler beds rest has been repeatedly observed to be grooved an ied, like *roches moutonnées*, and the direction in which the ic d has been determined in more than one locality. Unwillin ologists were to believe that there was a glacial period at thi stage of the earth's history, the evidence now in hand is over ning, and a glacial period in Australia in the late Carboniferou ermian period must be regarded as a demonstrated fact.[1]

he number of well-defined bowlder beds is in places (Bacchu h District, Victoria) not less than nine or ten, and some of them a thickness of fully 200 feet. The marine beds with which the ntercalated have an aggregate thickness of 2000 feet or more, 30 to 40 feet of coal are included between the highest and low f the bowlder beds. The recurrence of the bowlder beds point e repeated recurrence of glacial conditions, and the great thick both of clastic beds and of the included coal point to the grea tion of the period through which the several glacial epochs wer ibuted.

hese remarkable phenomena are not local. Counting Tasmania e glacial deposits are also found, the Paleozoic glaciation c ralia had a known range of nearly 22° in latitude (42° in Ta

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V. E. David, Q. J. G. S., Vol. LII, 1896, p. 289–301. "Glacial Action in Australi rmo-Carboniferous Time." Contains also references to all the literature o ibject.

eikie gives 3500 feet, op. cit., p. 1060.

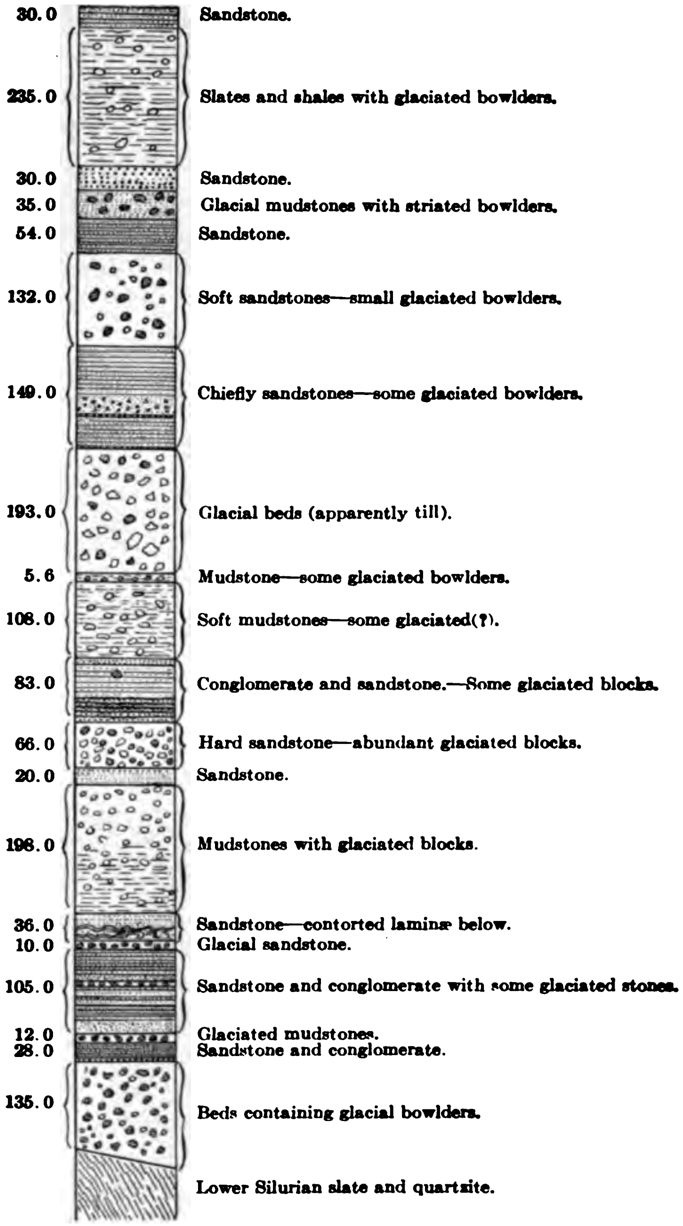
30.0 Sandstone.
235.0 Slates and shales with glaciated bowlders.
30.0 Sandstone.
35.0 Glacial mudstones with striated bowlders.
54.0 Sandstone.
132.0 Soft sandstones—small glaciated bowlders.
149.0 Chiefly sandstones—some glaciated bowlders.
193.0 Glacial beds (apparently till).
5.6 Mudstone—some glaciated bowlders.
108.0 Soft mudstones—some glaciated(?).
83.0 Conglomerate and sandstone.—Some glaciated blocks.
66.0 Hard sandstone—abundant glaciated blocks.
20.0 Sandstone.
198.0 Mudstones with glaciated blocks.
36.0 Sandstone—contorted laminæ below.
10.0 Glacial sandstone.
105.0 Sandstone and conglomerate with some glaciated stones.
12.0 Glaciated mudstones.
28.0 Sandstone and conglomerate.
135.0 Beds containing glacial bowlders.
Lower Silurian slate and quartzite.

FIG. 291.—Section showing the position and relations of the glacial beds in Australia. (David.)

ı to 20° 30′ in Queensland), and about 35° in longitude (wes 137° 30′), though it is not known, nor perhaps probable, tha e area within these limits was glaciated. On the other hand, to be understood that the phenomena here described are restricte ;h altitudes; rather are they known chiefly at low levels, descen ı some places nearly to the sea. The altitude of this region nly low now, but it was probably low during glaciation, as show .e relation of the glacial deposits to the marine beds. Whatev ifficulties in the way of its explanation, therefore, the fact of period, during which glacial conditions recurred many tim be accepted.

ıe marine beds associated with the glacial deposits seem to mat ›ximately those of the Carboniferous period elsewhere, but tl s of the associated coal show none of the most characterist of the Carboniferous beds as developed in Europe and Americ er do they present the general facies of the Triassic flora. (ther hand, Permian fish remains are found above all the bowld suggesting that the glacial conditions were over before the e e Permian, though in the same beds which contain fish remai have thought to see evidence of ice action. The glacial charact ese later beds has, however, not been proven. In any case th younger than the certainly glacial beds below. The testimo e plant fossils is therefore that the period of glaciation was la ıian or early Triassic; that of the marine fossils that it was la oniferous or early Permian. The better view, probably, is d the glacial beds as the base of the Permian.

ı some parts of Victoria, the Permian rests unconformably Lower Carboniferous. The glacial series is succeeded by co ng beds, and these by the Triassic system. The upper part system is coal-bearing also in New South Wales. The thickn ıe Permian in this region is some 13,000 feet.[1]

ıdia.—Overlying crystalline schists of great age, there is in t al part of the peninsula of India a system of rocks known as t lwána system. This system is made up of several divisio lowest of which (the Talchir) is formed in considerable part al conglomerate, the bowlders of which are sometimes as mu as four meters in diameter. Locally, the glacial series (the glacial beds and the formations interstratified with them) has a thickness of about 2000 feet.[1] The few plant fossils associated with this conglomerate are like those associated with the coal-seams of the glacial series in Australia. The age of these conglomerates is further indicated by the fact that they are overlain by the Fusulina limestone (late Carboniferous or Permian) comparable to that of Europe. Coal-beds, regarded as Middle Permian (the important coal-beds of India), also occur above the Talchir conglomerates in the Gondwána system, thus seeming to make them either late Carboniferous or early Permian.

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[1] Kayser Geologische Formationskunde, p. 265.

The character of the Talchir conglomerates, especially when studied in connection with the bed on which they lie, may fairly be regarded as demonstrating their glacial origin; for not only are the bowlders glacially striated, but the surface beneath the conglomerate, like the bed of the similar deposits in Australia, is also polished and striated.[2]

The glacial Paleozoic formations in India are in some respects even more remarkable than those of Australia, for they reach below the latitude of 18°, and are, therefore, several degrees within the Tropic of Cancer; not only this, but they occur at low levels, descending in places nearly to the level of the sea.

Conglomerates which appear to be of glacial origin are not limited to the Talchir formation of the peninsula. Similar formations, believed to be of the same age, appear in the Salt Range of India (Lat. 32°), in the central Himalayas, in Cashmere, and Afghanistan.

In the Salt Range, a marine Permian formation overlies the glacial series. Marine Permian is also known in northern Persia, Armenia, the central Himalayas, Tibet, central India, Timor, Yünnan, Nanking, and elsewhere.

South Africa.[3]—In South Africa there is a series of beds found in various parts of Cape Colony, Natal, Zululand, the Orange River State, and the Transvaal, which possess the same general characteristics as those of Australia and India. Here there are conglomerate beds (the Dwyka formation) some of which are glacial, and some of which

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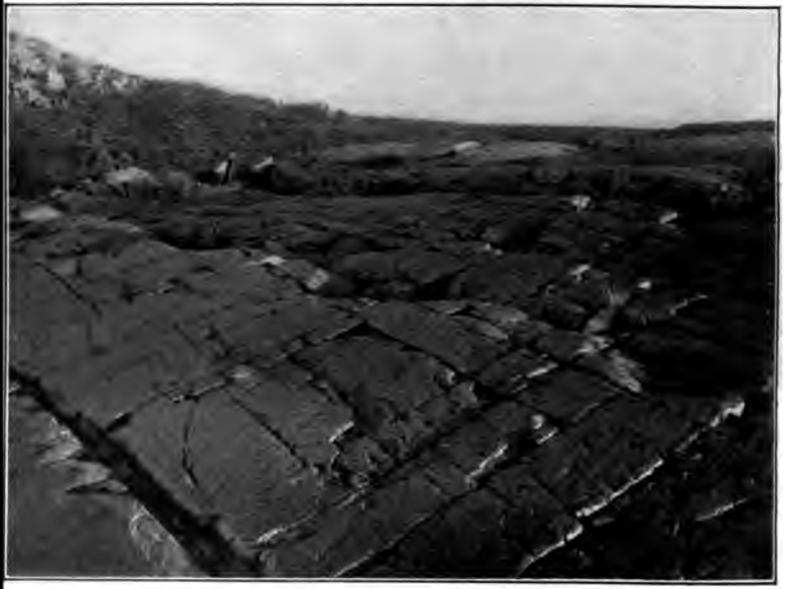
[1] Kayser, op. cit., p. 262.

[2] Oldham, Geology of India, 2d ed., 1893.

[3] For an excellent account of the Paleozoic glacial phenomena of these several regions, see C. D. White, Carboniferous Glaciation in the Southern and Eastern Hemispheres, Am. Geol., 1889, Vol. XIII, pp. 299–332. For a later account of the glacial beds, see footnote, p. 636. See also Geol. Cape Colony. Rogers, 1905, pp. 147–179.

probably deposited in water, in which bergs were floating.[1] The
lomerates are associated with strata (the Ecca shales) which a
red to the Permian system. Many of the bowlders of these co
erates are striated, and at the same time the bed on which t
ial conglomerate rests shows indisputable marks of ice acti
any places (Figs. 292 and 292*a*). The glacial beds are believ
ave extended as far north as 26° 40′ in the Transvaal. The glaci
associated beds have great thickness (1200 feet) in Cape Colony.



IG. 292.—Glaciated quartzite beneath the glacial conglomerate of South Africa. Near Prieska. The rock surface shows glacial striæ. (Schwarz.)

bove the Ecca shales, which are thought to be glacio-fluvial
io-lacustrine,[2] is the coal-bearing Beaufort series with Glossopte
and abundant reptilian remains.[3]

he known Permo-Carboniferous glaciation of Australia, Ind
Africa is found in two zones, the one north and the other sou
he equator. In neither zone have the limits of glaciation be

Scottish Geog. Mag., Vol. XVII, 1901, p. 57; and Trans. Phil. Soc. of
a, Vol. XI, 1900, p. 113.

Molengraaff, Bull. de la Soc. Geol. de France, 1901, p. 79.

Broom, Geol. of Cape Colony, pp. 228-244.

accurately determined, but in the former it is known to have extended from latitude 18° to about 35°, and probably still farther north, while in the latter it is known to have extended from latitude 21° to 35°. In an equatorial zone about 40° in width, glaciation has not been discovered. The glaciation of these various countries has a range of about 130° in longitude. Glacial conditions must, therefore, have prevailed over an area, or at least about the borders of an area many times as large as that covered by ice in the northern hemisphere during the Pleistocene glacial period.

The marked likeness of the floras associated with the glacial deposits throughout these three continents is believed to be evidence that there was land connection between them at the time of the glaciation. The horizons to which the Carboniferous types of plants are restricted, especially in Australia, have been thought to represent a lesser interval of time than that occupied in the deposition of the Carboniferous beds of Europe and America. Partly on this ground, the plant-bearing beds associated with the glacial deposits in Australia, and containing the Glossopteris flora, have been believed to represent the later part of the Carboniferous period; and if so, they indicate that the plant-life of this region advanced more rapidly than that of Europe and

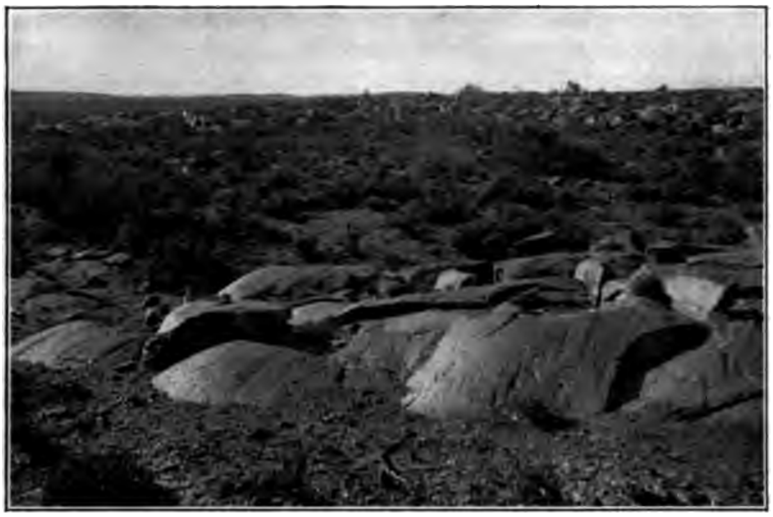


FIG. 292a.—North slopes of roches moutonnées. Near Prieska, South Africa. The rock surface shows glacial striæ. (Schwarz.)

erica, for the Glossopteris flora is allied to the Triassic flora of othe
ions. Since in all these regions the Glossopteris flora antedated
attended the glacial beds, it has been thought to be the flora o
ooler climate, and that this climate was the beginning of the chang
ich culminated in glaciation. As already indicated, the Carboniferou
Permian are not sharply differentiated in these countries. O
whole, the general relations seem to suggest that the beds con
ning the Glossopteris flora and the glacial beds were contempora

. 293.—Section of glacial conglomerate near Prieska. The conglomerate is ov
lain by Triassic shale. (Schwarz.)

ous with the early Permian of other regions, rather than with the C
niferous proper. If this be true, the culmination of the later Pal
c glaciation was in the early Permian. In the later part of t
iod there seems to have been an advance of the sea on the la
h in Europe and Asia (Salt Range of India).

South America.—Rocks like those of the countries about the Indi
an are also known in Argentina and the southern part of Bra
the latter situation, conglomerates of glacial aspect have long be
own. Their glacial character has now (1906) been proved by I.

ite.[1] Coal-bearing beds with the Glossopteris flora lie unconformably on older formations, and conformably below the Trias.[2]

CLOSE OF THE PALEOZOIC ERA.[3]

The close of the Paleozoic era was marked by much more considerable geographic changes than the close of any period since the Algonkian. These changes may be said to have been in progress during the Permian period rather than to have occurred at its close.

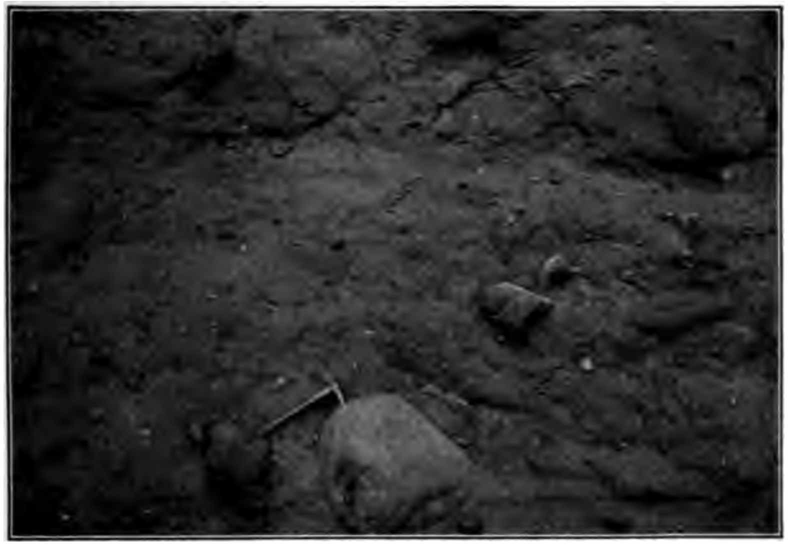


FIG. 294.—Section of glacial conglomerate (cemented till) near Prieska, South Africa. (Schwarz.)

The changes in the relations of land and water, and the deformation of strata mentioned in connection with the close of the Carboniferous period (p. 584), probably continued during the Permian.

It will be remembered that there was a considerable withdrawal of the sea from North America at the close of the Ordovician, converting large areas which had been submerged during the Cambrian

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[1] Geol. Soc. Am., Dec. '06.

[2] Kayser, Geologische Formationskunde, p. 265. This author states, pp. 227 and 265, that glacial beds occur in South America.

[3] Smith, J. P., Jour. Geol. Vol. IX, pp. 512–21.

Ordovician periods into land; but as the Silurian period pro-
ed, the sea gradually crept back over much of the area from which
d temporarily withdrawn. Of the larger part of this area the
etained possession through the later part of the Silurian and
Devonian periods, and during the Mississippian it was greatly
ded.

the Coal Measures period great areas were converted into marshes,
till later in the period, or at its close, a wide-spread withdrawal
sea made most of the area of the United States east of the 96th
lian, land. The geographic changes may be best appreciated by
aring the maps on pages 497 and 545. The movements which
ed in these changes were probably slow, and for most of the
not notably deformative.

he great geographic changes which had been accomplished, or
lvanced, by the close of the Paleozoic, were (1) the development
e Appalachian mountain system at the western border of Appa-
a; (2) the deformation of the surface of Appalachia; (3) the
opment of the Ouachita mountains; (4) the final conversion
larger part of the area between the Great Plains and Appalachia
an area of deposition to an area of erosion; and (5) the restriction
e west of the area of sedimentation in the western interior.

ich extensive geographic changes, involving the conversion of
great areas from sea bottom into land, must have caused pro-
l changes in the circulation of water, in climate, and in the dis-
tion of terrestrial and marine life.

THE LIFE OF THE PERMIAN.

he life of the Permian can carry its full meaning and receive its
nterpretation only when put into association with the extraor-
y physical conditions which formed its environment. These were
most remarkable in the post-Cambrian history of the earth.
een them and the life there must have been reactions and adapta-
of the utmost significance, if we could surely read them. At no
d, save our own, were the phenomena so pronounced, and hence,
little doubt, so rich in possible instruction as to the adaptation
e to extreme conditions. Their teachings have been less eagerly

ught and less freely received than they merit, because of preva-
nt preconceptions as to what *must* have been the state of the atmos-
here and the type of life, arising from a single unquestioned hy-
othesis of the early state of the earth and its necessary sequences.
alternative views on this fundamental subject are entertained,
e psychological conditions will be more felicitous for following to
eir legitimate conclusions the extraordinary facts of this critical
eriod.

Because the physical conditions were so pronounced in the salient
atures of glaciation and aridity, certain questions relative to the
fe at once arise: (1) Was it possessed of such powers of adaptation
at it met its extraordinary environment by accommodating itself
it; or (2) was it destroyed co-extensively with the changes in envi-
onment; or (3) did it elude the adverse conditions by shifting from
ne area to another as the adverse conditions shifted (hypothetically);
r (4) did its composite experience embrace all these, and if so, what
easure of each?

The impoverishment of life.—There is no question but that there
as a great reduction in the amount of life. In the earlier days of
eology, it was commonly held that a complete destruction of all living
hings on the face of the earth attended this closing period of the Paleo-
oic era, and that a re-creation followed; for in the state of knowledge
f that time, no Paleozoic form was known to occur in the following
ra. Had it then been known that glaciation pressed upon the bor-
ers of the tropics on either side, in the far Orient, and that intense
ridity dominated large areas elsewhere, it would have added great
trength to the conviction of a universal catastrophe to life. With
he progress of investigation, however, no small relief from the adverse
ata has been found in the discovery that some forms bridged the
nterval, and in the additional grounds for belief that many others
nderwent modifications which enabled them to pass it as new types,
nd in the accumulating evidences that the succession of life was
nbroken, though greatly modified. Progressive investigation is still
ringing forth more and more evidence of this kind, and reducing
he disastrous implications of the record. Not only this, but wide study
rings into view the compensating effects of the strenuous conditions
n calling into play the latent powers of adaptation and of resistance
f the organisms, and in producing new forms of life. Notwithstand-

the *Schizoneura* branch of the family also was represented. *Sphenophyllum* held on into the period chiefly by new species. While some of the more persistent genera of Coal Measure ferns or *Cycadofilices* were represented by new species, the majority disappeared, and new genera took their places, *Callipteris*, *Tæniopteris* and *Cymoglossa* being especially significant of the new order of things. Of the older genera, *Pecopteris* was especially prolific in species, and *Sphenopteris* and *Goniopteris* were well represented. Just how many of these frond-genera were true ferns and how many *Cycadofilices* remains to be determined, but we are warranted in noting the singular fact that the fern-stock survived changes with more success than most of its contemporaries. The *Cordaites* continued, and initial forms of the ginkgos appeared in *Saportea* and *Baiera* and gave a Mesozoic forecast to the flora.

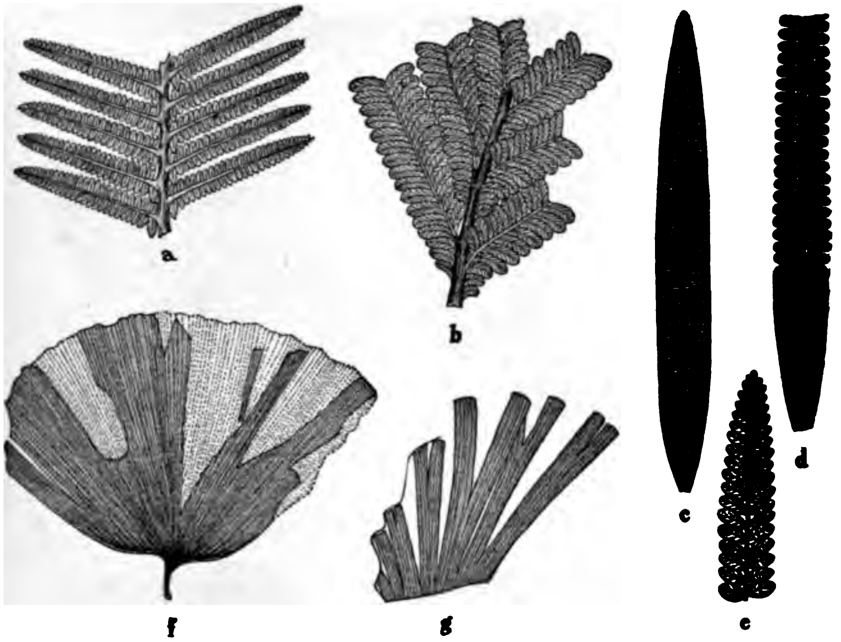

FIG. 295.—PERMIAN FLORA OF AMERICA: *a*, *Pecopteris tenuinervis* Fontaine and White; *b*, *Callipteris conferta* Bgt.; *c*, sterile frond of *Tæniopteris newberriana* Fontaine and White; *d*, *T. newberriana*, basal part of a fructified frond; *e*, *Cymoglossa obtusifolia* Fontaine and White; *f*, *Saportea salisburioides* Fontaine and White; *g*, *Baiera virginiana* Fontaine and White.

In Eu[illegible] most of the above forms appeared rather sparsely at

ening of the period, and gradually increased in prevalence, wh
sidual Carboniferous species declined. The general aspect

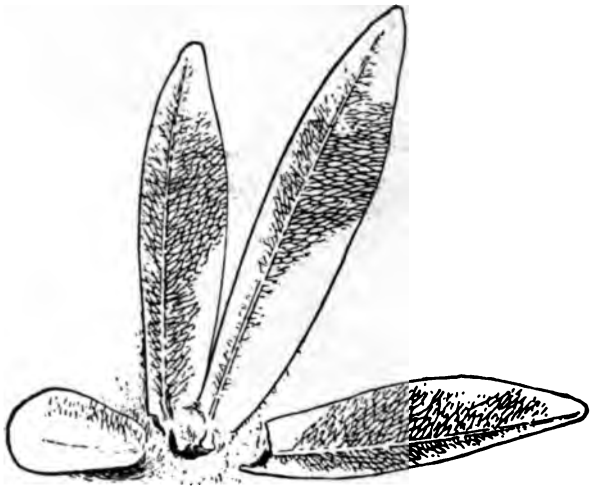

FIG. 296.—A verticel of leaves of Glossopteris. ×2. (After Etheridge.)

lora remained, however, that of poverty. Two new types
interest came in and became characteristic, *Walchia* and *Voltz*
ia (Fig. 297) resembled an Araucarian conifer in its folia
ts seed organs were apparently different. While conifers ha

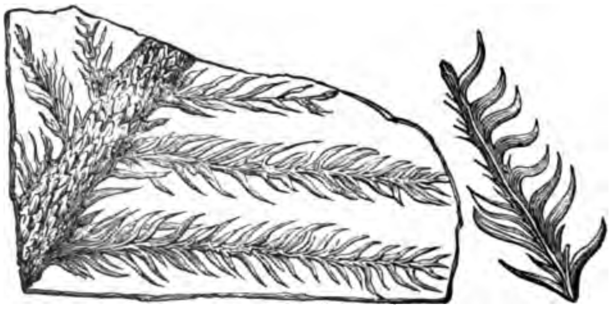

FIG. 297.—*Walchia piniformis*, a Permian conifer of Europe.

reported from earlier systems on the doubtful basis of woo
, *Walchia* may probably be safely regarded as representing the

It had small bract-like leaves closely and thickly attached to the limbs, giving it a scrawny appearance. *Voltzia* (Fig. 298, *h*) is interesting as a supposed forerunner of the group (*Cryptomeria*) to which the giant sequoia and the bald cypress belong. The abbreviated leaves and pauperitic aspect of both *Walchia* and *Voltzia* will be noted.

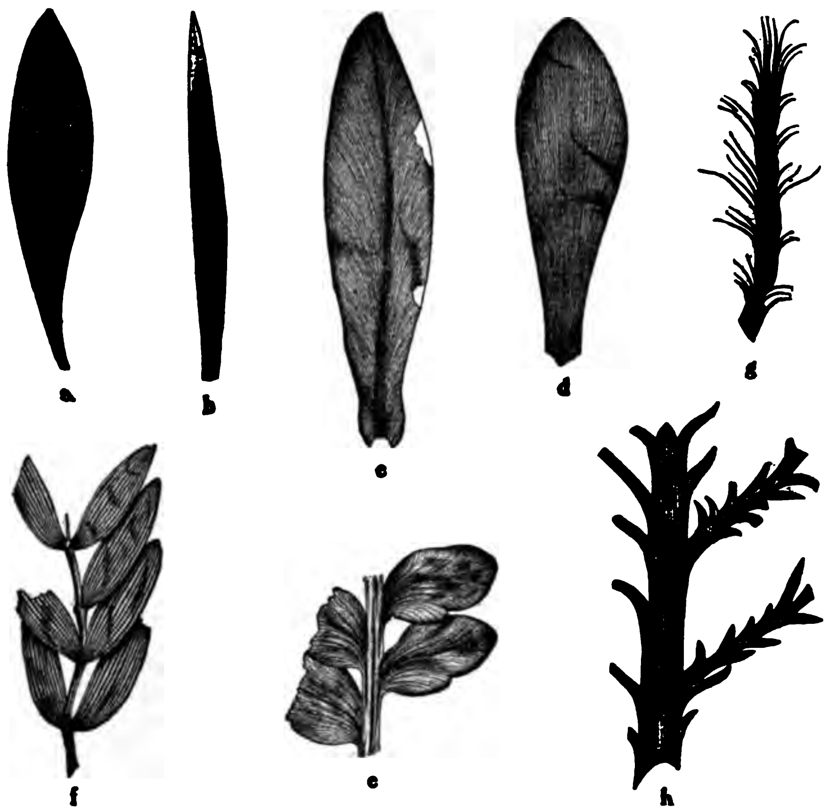

FIG. 298—REPRESENTATIVE TYPES OF THE GLOSSOPTERIS FLORA: *a, Glossopteris communis*, Fstm.; *b, G. angustifolia*, Bgt.; *c, Gangamopteris cyclopteroides*, Fstm.; *d, Noeggerathiopsis hislop*, Bunb.; *e, Neuropteris valida*, Fstm.; *f, Schizoneura gondwanensis*, Fstm.; *g, Phyllotheca indica*, Bunb.; *h, Voltzia heterophylla*, Bgt.

The Glossopteris flora.—The most remarkable vegetal event of the period was the evolution of the *Glossopteris* (tongue-fern) flora in the southern hemisphere, and its migration into the northern. The representative members of this flora were the ferns *Glossopteris, Gan-*

teris, *Noeggerathiopsis*, and *Neuropteris*, the equisetales *Phy*
and *Schizoneura*, and the conifer *Voltzia* (Fig. 298, *a-h*), tl
two being eminently characteristic. The peculiar expressi
group will at once be recognized, especially the simplicity
tlines of the fern leaves, and their contrast to the usual dissect
, as also the pauperate aspect of the *Voltzia*. These give suppo
view that this flora was evolved to meet the adversities of c
which prevailed in and about the glaciated regions. While tl
of this flora do not actually appear in the glacial beds ther
, they are found in tne interglacial deposits, and in those th
mediately above the upper glacial beds. Developed thus am
se surroundings, if not directly under adverse conditions, tl
not only took on a resistant aspect in simple outlines and cor
orms, but soon gave evidence of its vitality by spreading nortl
into east Africa and Asia, and then Europe.[1] It reached norther
in the latter part of the Permian period (Amalitzky), whe
associated with *Callipteris* and other forms typical of the Eur
Permian flora. It is also found in Brazil and Argentina. I
y is further shown in that its descendents became a dominar
e in the Mesozoic floras that followed.

II. The Land Animals.

e **Amphibians.**—Relatively, the amphibians reached their mos
ed supremacy in the latter portion of the Carboniferous perio
hey may have been then actually at their numerical climax, f
onditions were apparently extremely favorable for them. The
ued, however, to be a prominent feature in the early portio
Permian at least, but they probably declined in the later portio
the less favorable physical conditions then prevalent, suppl
d by the attacks of the predaceous reptiles that had entere
rena. At any rate they were overshadowed in historical si
nce by the rise of the reptiles, without doubt their descendent
Permian amphibians were of much the same types as befor
some advances in organization, and some reptilian tendencie
e **appearance of the primitive reptiles.**—While the reptiles prol

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[1] Amalitzky, Schrift d. Warschauer natur. Ges., 1895–1900.

ably began to differentiate from their ancestral amphibians earlier than the Permian, the first demonstrable relics as yet found are from the lower strata of this period. Before its close, there had appeared a large and complex group of primitive reptilian forms very curiously related to one another, implying that they were yet in the early stages of their differentiation, and hence still retained various common inheritances from their ancestry, and implying also, probably, that they were affected by parallel evolution. There were, at the same time, signs of profound divergence. Two great branches seem already to have been defined in part; perhaps indeed they had never formed a common group, as reptiles, but had parted company while yet they were amphibians. The one (essentially the *Diapsida* of Osborn)[1] bore resemblance to the microsaurians and may have descended from them or from allied forms. In the earliest phases represented, they had already attained a decidedly reptilian structure of the rhynchocephalian type. They seem to have been the forerunners of the great hosts of lizards, crocodiles, dinosaurs, ichthyosaurs and flying saurians that constitute the most declaredly reptilian line; not that these were all necessarily descended from the Permian rhynchocephalians, but they form a great group marked by certain analogous features, implying either kinship in genesis, or kinship in evolution.

The other group (*Synapsida*) bore skeletal resemblances to the highest labyrinthodonts, on the one side, and to the lowest mammals that appeared later (*Monotremes*), on the other, and hence may be regarded as constituting the mammalian strain of the ancestral reptiles. In their earliest known phases they were rather anomalous, and later they deployed into a remarkably complex order (thero-

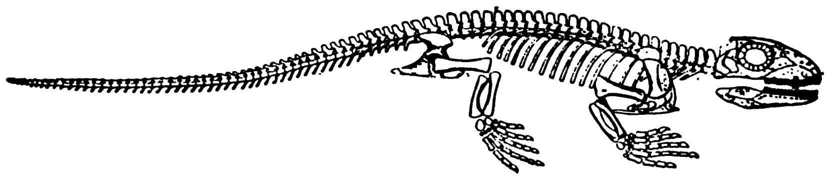

FIG. 299.—*Palæohatteria longicaudata*, a primitive diapsidan of the order *Protorosauria*, about ⅓ natural size. (Restoration by J. H. McGregor.)

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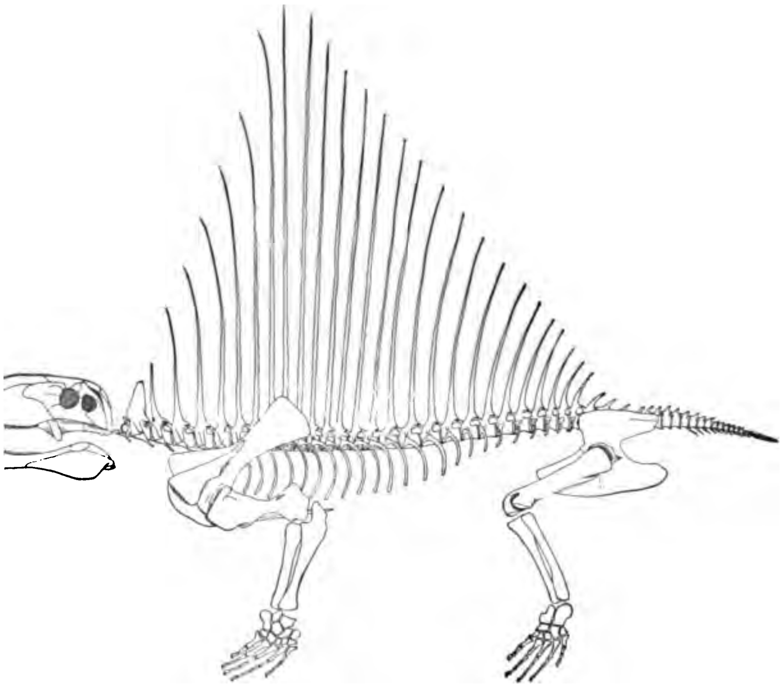
[1] Science, Vol. XVII, No. 434, 1903, pp. 275–276.

ıs or anomodonts) whose relationships and significances yet resolution, for the greater part. Under the theromorph lineage erhaps to be placed the turtles and plesiosaurs that appeared The more generalized or stegocephalian-like forms of the latter have been given an ordinal rank as the *Pareiasauria* or *Cotylo-ı* by some authors, who regard them as ancestral not only to *Theromorpha*, but to the rhynchocephalian type of reptiles as thus giving expression to the view that the differentiation had



00.—A fin-back lizard of the Permian of Texas (*Dimetrodon*). The skeletons found vary from three to ten feet in length. (Restored by Case.)

red after the attainment of the reptilian form. Other group-ıre made by other authors, implying that a final opinion is not ıniversally reached.

ıe more distinctively reptilian group (Diapsida).—The *Palæohatteria* Lower Permian of Saxony, a small, long-tailed, lizard-like reptile, ognized at present as the pioneer of this branch (Fig. 299). It was typically rhynchocephalian, and is notable in that its line of descent is perpetuated to this day in the *Sphenodon* or *Hatteria* of New Zealand. With kindred genera it constitutes the suborder *Proterosauria.* Representatives have been found in England, Scotland, France, and Bohemia. They are not known in North America. An allied suborder (*Pelycosauria*) is predominantly American, and was represented by several genera (*Clepsydrops, Embolophorus, Dimetrodon, Naosaurus,* etc.) in Texas, Illinois,[1] and Kansas. There were also representatives in Europe. The skeletal features of one of the more typical genera, as worked out by Case, are shown in Fig. 300. A third suborder (*Proganosauria*) which some paleontologists believe to be rhyncocephalian in character, though by others referred to the *Sauropterygia,* had two genera (*Stereosternum* and *Mesosaurus*) of small, elongate, subaquatic reptiles (Fig. 301), from Brazil and South Africa.

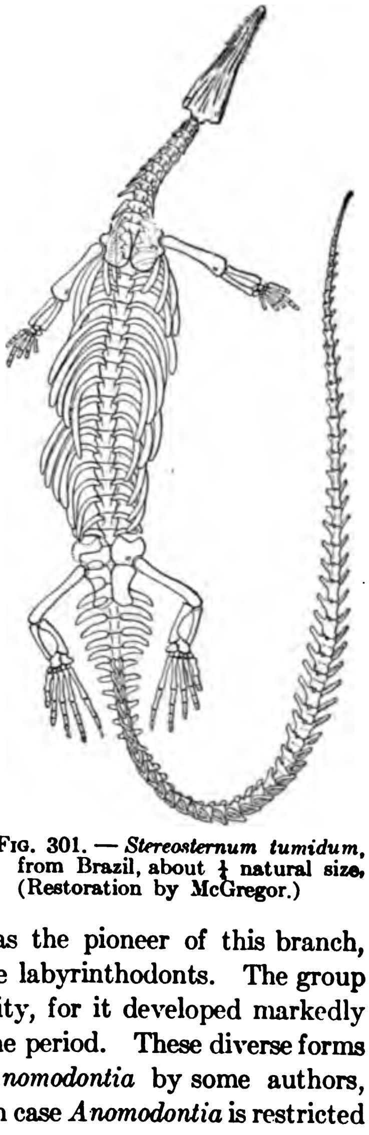


FIG. 301. — *Stereosternum tumidum,* from Brazil, about ¼ natural size. (Restoration by McGregor.)

The mammalian strain of the reptilian group (Synapsida). — At present the *Pareiasaurus* (Fig. 302) stands as the pioneer of this branch, and presents the nearest approach to the labyrinthodonts. The group seems to have diverged with great rapidity, for it developed markedly varied and strange forms by the close of the period. These diverse forms are grouped under the ordinal term *Anomodontia* by some authors, and by others under *Theromorpha,* in which case *Anomodontia* is restricted to a suborder (=*Dicynodontia*) under *Theromorpha.* The latter term

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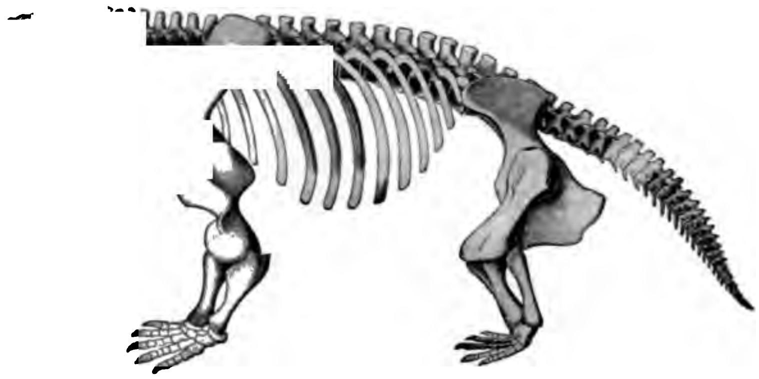
[1] The locality in Illinois appears to be simply an old river-bed eroded in the surface of the Coal Measures, and subsequently filled with alluvium, imbedding the reptilian remains.

to the mammalian features, the former to the peculiar dent
The theromorphs deployed into four suborders, and becan
lominant group among the earliest reptiles in each quarter
globe where they have been discovered.[1] The most primiti
suborders was the *Pareiasauria* or *Cotylosauria*, by many paleo
ists now considered of ordinal rank, whose type family includ
pioneer genus above illustrated. This family was abundant
sented in South Africa and in several parts of Europe, notab



02.—*Pareiasaurus* ***serridens***, **of Cape Colony, S. Africa, Karoo formatio**
× about $\frac{1}{25}$. (After Broom.)

ern Russia, where Amalitzky has recently found many skeletons
family is not known in America, but two other pareiasauria
ies are represented by several genera (*Otocœlus, Pariotichu
tes, Pantylus, Hypopnous, Empedias, Diadectes, Chilonyx, Bo*
). This distribution is very notable, considering the early sta
olution of the reptiles.

ie reptiles grouped under the suborder *Theriodontia* posse
iar interest because of the mammalian aspect of their skulls, of the
tion, and of many features of their skeletons (Fig. 303). The
especially abundant in South Africa (Karoo beds[3]), but the
been found also in Bohemia, and notably in Russia (Amalitzky

. S. Woodward, Vert. Pal., p. 144.

ompt. Rend., March, 1901.

is well to bear in mind that the Karoo beds, so wonderfully rich in significa
rate remains, are regarded as Permian in part and Triassic in part, and th
ion of their theromorphs belong to the latter. See also Broom, Geol. of Ca
, 1905, pp. 228–249.

The anomodonts, in the restricted sense (=dicynodonts), were highly specialized forms notable for their toothless jaws, or else jaws with single tusk-like teeth. The rest of the jaw was protected by a horny covering such as turtles have. Some features of their skulls also were curiously chelonian in aspect, and there may have been a genetic relation between the anomodonts and the turtles; but the evidence at present does not go beyond resemblances. The dicynodonts were probably herbivorous. The Karoo formation of South Africa has yielded them in greatest abundance, and they have also been found in India, Russia, and Scotland.

It is not certainly known that the fourth suborder of theromorphs, the *Placodontia*, were represented in the Permian, though their presence is probable. They were remarkable for their singularly modified dentition which has no parallel among reptiles. The teeth in front were conical, but the jaws elsewhere, and the palate, bore large molar-like grinding teeth. They are thought to have been allied to the ancestral turtles. These anomalous departures in dentition may have had some relation to the peculiar developments of the vegetation under the stress of the late Permian and early Triassic climatic conditions.

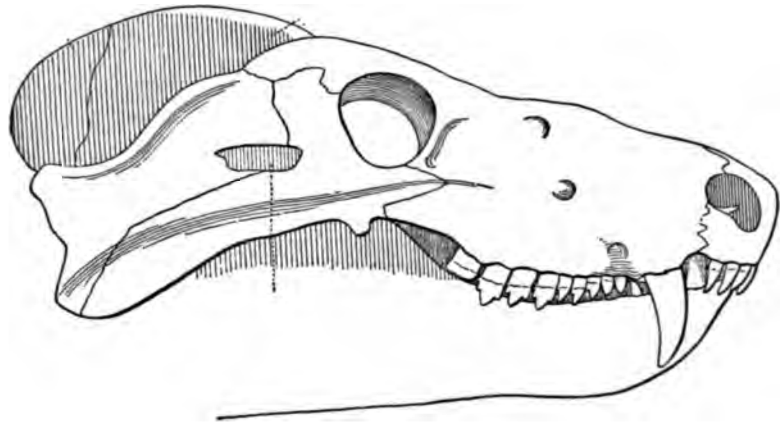


FIG. 303.—View of the right side of the skull of the theriodont *Cynognathus crateronotus*, from the Karoo formation, South Africa, showing the striking resemblance of the teeth and skull to a mammalian carnivore.

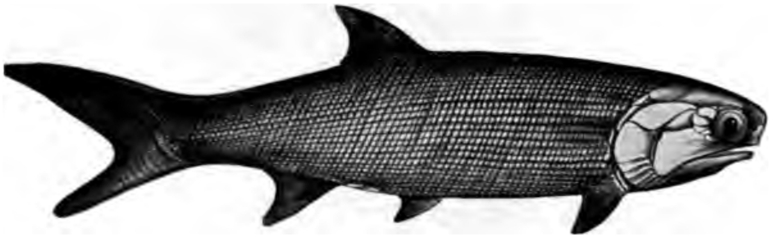
This rapid and diverse deployment of the early reptiles in a period of general life impoverishment is not a little remarkable, but as it was

rolution of air-breathers, the key to it may lie in a more oxygenat
ısphere, a point to which we shall return.

he scant record of other land forms.—The Permian record
ırthropods and of the terrestrial mollusks is very poor, and prc
represents an impoverished state of these classes, but local exc
will doubtless yet be discovered.

III. *The Fresh-water Life.*

'he amphibians and some of the reptiles constituted, in a sen
rtion of the fresh-water as well as the land life. Besides the
s were abundant, locally at least. The beautiful little *Paleonisc*
304) seems to have had its climax here, and almost disappear



304.—A Permian fish, *Paleoniscus macropomus*, from Thuringia. (Restorat
by Traquair nearly one-half natural size.)

e close of the period. Fishes of similar structure, but with de
oodies, belonging to the *Platysomus* family, Fig. 305, were abunda
modern aspect of these fishes will be noted. With these w
genera that had been prevalent before. Their associations sh
they lived in fresh waters, but they may also have lived in t

here were fresh-water mollusks, some of which resembled uni
arthropod element was not well represented, though, so far
n, it shows but little change from the Carboniferous.

IV. *The Marine Fauna.*

he withdrawal of the epicontinental seas from considerable p
of the continents necessarily reduced the territory availa
ıallow-water life, and introduced a restrictional evolution. Th
therefore at this time a coincidence between impoverishment

land, and restriction in sea, when normally the relations are reciprocal. In North America, the restricted marine area lay in the tracts just previously occupied by the expanded Carboniferous seas, and inherited its fauna from them. At first nearly all the species were the same as those of the preceding period, and hence a grave difficulty has always been experienced in drawing a dividing line between them. Prosser, who has carefully studied the Permian of the great plains, has recently listed the known species, and found only about seventy. This suggests a decadent fauna. Of these, about one half are pelecypods, which is doubtless a response to the increasing turbidity that attended the shallowing of the sea. Representative forms are shown in Fig. 306, *g–j*. Gastropods (Fig. 306, *k*), brachiopods, and cephalopods (Fig. 306, *a–f*) make up the larger part of the rest. Generally, the productids were the most characteristic forms, and the long-lived, cosmopolitan *Productus semireticulatus* frequented the seas in all quarters of the globe. It was the last flourishing stage of the productids, as well as of the orthids, the spirifers, and the athyrids, though the last two eked out a lingering existence till the Jurassic period.

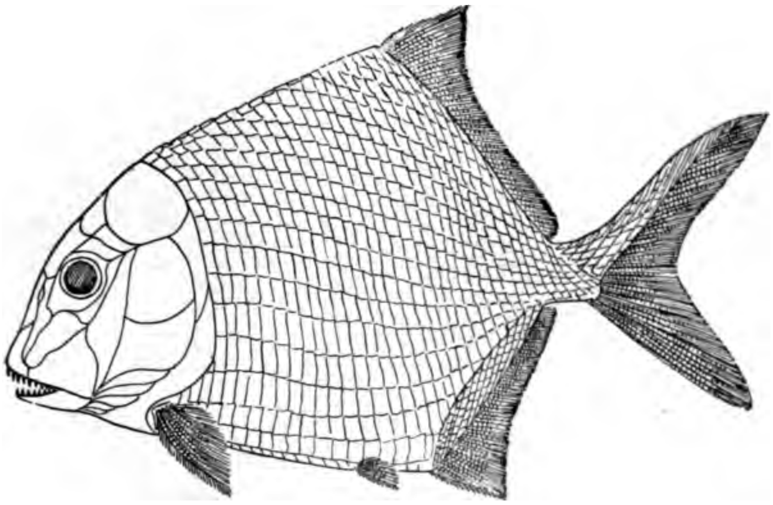
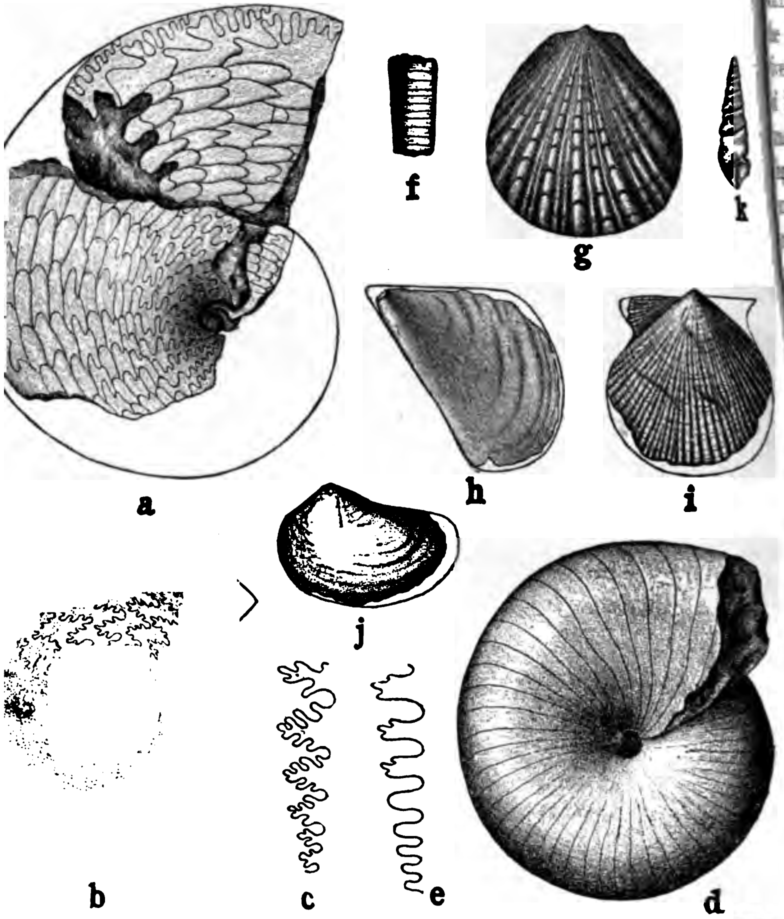


FIG. 305.—A Permian fish, *Platysomus gibbosus*, restoration by Traquair, about one-fourth natural size. Germany and England. (Woodward.)

The advent of the ammonites.—The increasing complexity of the sutures of the coiled cephalopods has been noted in previous periods. In the goniatites of the Middle Devonian, the sutures had become

lexly lobed. A transition from the simply lobed goniatites
with more complicated sutures had taken place as far back
Kinderhook epoch (see Fig. 235, *j*). In the latter part of



)6.—The Marine Permian Fauna: *Cephalopoda: a*, ***Medlicottia copei*** White; .nd *c*, *Waagenoceras cumminsi* White; *d* and *e*, ***Popanoceras walcotti*** White; ee forms of ammonoids with more complicated sutures than were present in lier forms; *f*, *Orthoceras rushensis* McCh., one of the last of the orthoceratites. ecypoda: *g*, *Pseudomonotis hawni* (M. & W.); *h*, *Myalina permiana* (Swall.); *i*, iculopecten occidentalis (Shum.); *j*, *Sedgwickia topekaensis* (Shum.). *Gastropoda:* rchisonia sp.

ian period, forms with still more intricate sutures (Fig. 306, *c* and proaching those of the characteristic ammonites of the Mesozoic, ne conspicuous. The genera *Medlicottia* (Fig. 306, *a*), *Waageno-*

ceras (Fig. 306, *b* and *c*), and *Popanoceras* (Fig. 306, *d* and *e*) were representative types, occurring in America, Europe, and Asia. The older types of coiled cephalopods, the goniatites and nautiloids, mingled with these newcomers. Interestingly enough, there was also present the ancient straight form *Orthoceras* (Fig. 306, *f*), now reduced to primitive simplicity and diminutive size, lingering along in the last stages of its prolonged career, to finally disappear in the Trias. The contrast (compare Fig. 306, *f*, with *a*, *b*, and *d*) between the disappearing straight type, in its depauperate form, and the robust, youthful ammonites, about to become a ruling dynasty in its stead, is most marked. It was in this, as in not a few other cases, a Permian function to welcome the coming and speed the parting guest.

The retreatal tracts of the marine life.—As in previous transition epochs when epicontinental waters were largely withdrawn, the marine faunas found special refuge in certain embayments or border tracts which, in connection with the coastal belts, permitted them to re-form themselves, re-generate their species, and prepare for a succeeding invasion of the continental areas. On the American continent, the St. Lawrence embayment had done repeated duty in this line, but there is no specific evidence that it participated notably in the Permo-Triassic transition. The border of the Gulf of Mexico, the Mediterranean tract, notably in the region of Sicily and southeast Europe, and the Ganges-Indus tract of southern Asia, seem to have been special areas of refuge and regeneration. There are signs of another in northern Asia, and suggestions of still another in an unknown region from which the Triassic invasion of the *Tropitidæ* came. In these and doubtless other tracts, and on the continental borders generally, the shallow-water marine faunas passed from the Paleozoic to the Mesozoic phases. The restriction, compared with the expansional stage of the Mississippian period, was extremely severe, but the faunas emerged with new species born in adversity, ready for conquest when the re-advancing seas should give them an expanding realm.

THE PROBLEMS OF THE PERMIAN.

Between a marvelous deployment of glaciation, a strangely dispersed deposition of salt and gypsum, an extraordinary development of red beds, a decided change in terrestrial vegetation, a great depletion of marine life, a remarkable shifting of geographic outlines, and a pronounced stage of crustal folding, the events of the Permian period constitute a climacteric combination. Each of

phenomena brings its own unsolved questions, while their combination
ıts a plexus of problems of unparalleled difficulty. More than any other
. since the Proterozoic, the Permian is the period of problems. With little
these marked phenomena were related to one another, and their eluci-
ı is quite sure to be found in a common group of cooperative agencies.
it is too much to hope for a full elucidation at once, there is no occasion
nk the facts or evade the issues they raise.

st, however, we push our emphasis of these phenomena too far, let it be
that none of the factors in this combination were wholly new to geological
y. There had been glaciations almost as strange in early Cambrian or
ımbrian times (Norway, China, South Africa); there had been signs of aridity
salt and gypsum deposits of Silurian and other early times; there had
prevalent red beds in the Old Red sandstone and in the Keweenawan;
had been marked restrictions of life at the close of the Ordovician and
er stages; there had been extensive geographic changes in earlier Paleozoic
s; and there had been foldings of surpassing intensity in Archean and
ozoic times. The peculiarity of the Permian combination was its unusual
exity, the extraordinary intensity of the glaciation, and the aridity.

ıe chronological setting of the combination lends some advantages to its
. It lies in the midst of geologic history, with periods of great uniformity
emarkable polar geniality both before and after it. No appeal can be
to a supposed final refrigeration of the earth, or to any declining stage
ıile condition. It was an episode in the midst of a long history, with
probability that it was not without predecessor and successor, though
may not have been so marked.

portion of the phenomena were direct expressions of deformation, others
seemingly close sequences of deformation, while still others may be only
ore remote sequences of deformation in the form of changes of atmospheric
ydrospheric constitution. If the solution of these problems lies wholly
estrial causes, it seems at present most likely to be found in the immediate
lterior consequences of deformation, as realized in physiographic changes,
ı the constitution and working conditions of the hydrosphere and atmos-
Without assuming that this is necessarily so, this line of inquiry, yet
infancy, may be outlined.

I. *The Deformation.*

e deformation at the close of the Paleozoic appears to have been typical
t it involved an increase in the capacity of the oceanic basins and the with-
l into them of most of the previous epicontinental waters, while at the
time the continents were rendered slightly more protuberant by being
arched or warped throughout the larger part of their areas, and, in cer-
mited tracts, accidented by sharp folding of the external shell. So far as
t evidences go, the more pronounced arching and folding was felt chiefly
borders of the continents adjacent to the north Atlantic, but this apparent
.ion may be due to the imperfection of existing knowledge. Such limita-

tion is not, however, out of harmony with what is known of other great deformative movements, for in these, as a rule, the more intense foldings seem to have been concentrated along restricted tracts.

Some of the dynamic conceptions involved in such a general deformation have been previously discussed (Chapter IX, Vol. I, and Chapter II, Vol. II). In special application here, it may be noted that during the Subcarboniferous and Carboniferous periods, in eastern America at least, a stage of approximate base-level seems to have been developed over some considerable portion of the territory, as shown by the configuration of the surface upon which the deposits of these periods encroached, and there is reason to believe that this condition was a rather general one. So far as can be judged from available evidence, this conception may be extended to all of the continents; indeed, this conception is almost necessarily involved in the wide transgression of the seas of these periods. This conception involves almost necessarily, as its essential prerequisite, the further conception of a protracted period of relative quiescence, for in such a period only could base-leveling be accomplished. It is presumed that during this period of quiescence, the energies that were to actuate the subsequent deformation were accumulating stresses preparatory to actual movement, for, in so far as loss of heat was one of the agencies, such loss must have been in progress; in so far as the internal transfer of heat was concerned, it also should have been in progress, and in so far as molecular changes were involved, they may be supposed also to have been going forward, or to have been acquiring the conditions prerequisite for action. It is, therefore, conceived that during the quiescent stage, stresses were progressively accumulating in the body of the earth, but that they only reached an intensity superior to the earth's resistance after a protracted period. When at length they surpassed all resistances, deformation went slowly forward until the stresses were, in the main, relieved, and the earth was thus prepared to relapse into another stage of relative quiescence. Considerations that have been previously presented make it appear probable that a large portion of the body of the earth was involved in the deformative movement, for, among other reasons, the portion of the crust which was folded had very feeble powers of resistance and cannot reasonably be supposed to have, of itself, accumulated stresses of the magnitude implied by the actual deformation. The phenomena seem to point to a high state of rigidity in the great body of the earth, and to the accumulation of very widely distributed stresses which were feeble at every point, and which only acquired effective strength by their ultimate union in a common movement.

The essence of the movement may be assumed, with much confidence, to have been a shrinkage of the earth, preferably a general and deep-seated shrinkage, rather than a purely superficial one. The shrinkage in the sectors beneath the ocean basins is presumed to have been slightly greater than that in the continental sectors, because of the superior specific gravity the sub-oceanic sectors are assumed to have acquired from their ancestral history, and because of their loading by the ocean, and by the sediments brought down from the land during the previous periods. At the same time, the removal of the sedimentary mate-

om the land lightened the continental sectors and tended to disturb the ›e between them and the oceanic sectors. The superior shrinkage of the c sectors thus caused was probably attended by some crowding upon the r continental sectors between them, which appears to sufficiently account e slightly increased protuberance of the continental platforms, together he gentle warpings which they manifest, while the increase in the basin ty resulting from the subsidence of the ocean bottoms accounts for the rawal of the epicontinental waters. The outer shell of the crust, being ınd not under a load equal to its rigidity, appears to have accommodated to the shrinking interior by lateral shear and folding concentrated into , instead of by a more distributive crumpling, or crushing. In this lateral and folding is found the explanation of the post-Carboniferous mountains of n North America and western Europe, and such similar foldings as may ps have taken place in other regions at this time.

II. The Immediate Sequences of the Deformation.

erference with circulation.—It is obvious that the withdrawal of the extenheets of water which had submerged the continents to the extent of per-20,000,000 or 30,000,000 square miles, resulted in a serious restriction of ›eanic circulation, and correspondingly reduced the effects which such a ıl circulation had upon the climate of the times. These effects were probprofound. The surface temperature of the oceanic waters of the Mis-›ian and Carboniferous periods may, without any pretension to accube assumed to have been 25° C., or some such figure, as against the present

The submerged remnants of the continental platforms, while they must interfered somewhat with the general oceanic circulation, probably did far interrupt it as to prevent the polar regions being warmed by a most ve water-heating system. No small factor in this, perhaps, was the deep ıtion of the ocean, a matter of vital moment in all climatic studies.

the discussion of the Pleistocene glaciation the possibility of the reversal deep-sea circulation by means of a change in the relative influence of the ıtration of salinity by evaporation in the low latitudes on the one hand, and reased density due to the low temperature in the high latitudes on the is entertained and its bearings discussed.

e deep oceanic circulation is now dominated by the *polar* temperatures, is the cold waters of the polar regions that, descending and flowing toward ıuator, control the temperature of the deep sea. This is now low because low temperature of the polar regions; but if the circulation of the Subiiferous, and Carboniferous periods, whatever its nature, kept the polar s at a mild temperature, the great body of the deep sea must have had ratures correspondingly higher, and the water must have had so much the ›pressing influence on the temperature when it rose to the surface. This have contributed to the widespread warmth which the Subcarboniferous, ·rhaps the Carboniferous, period enjoyed. The mildness of the polar climates in these and several other periods, before and since, is one of the most remarkable climatic features of geologic history. The crucial feature is the maintenance of a mild temperature throughout the long polar night. Almost the only approach to a satisfactory solution seems to lie in a warm oceanic circulation, blanketed by a heat-retaining atmosphere, in which vapor of water and carbon dioxide, abetted by a prevalent mantle of clouds generated by the warm ocean, conjoined their equalizing and conservative influences.

The transition from the Subcarboniferous to the Permian involved a change from an effective circulation of warm water to an interrupted circulation which limited the previous equalizing and conservative influences. This was one step toward a lowering of the polar temperatures, which perhaps ultimately reached the amount of 20° C. or more, and toward a lowering of the temperature of the great body .of the ocean through the deep-sea circulation initiated and controlled by the polar temperatures. This was a step in the differentiation of regional temperatures, and this, as we shall proceed to note, was abetted by several other agencies arising from the same fundamental source, deformation.

Topographic sequences.—As already indicated, the deformation resulted directly in a pronounced change in the topography of the continents, in that it gave marked relief to the portions that were sharply folded, and a less declared but appreciable relief to the portions that were bowed upwards more gently. Both resulted in an increase of the general gradients of the surface, and hence in a rejuvenation of the streams. The increased area of the land obviously increased the number and the length of the trunk streams, and added to the volume of water that flowed through them, qualified, to be sure, by the aridity that followed. An inevitable result of these changes was a more rapid removal of the residual earth that had doubtless accumulated during the previous low-lying stages, and, following this removal, a dissection of the underlying formations and a lowering of the ground-water. An inevitable attendant of these sequences was an increased contact of the atmosphere with unleached rocks, combining at once the effects of the increased land area, the removal of the residual mantle, the dissection of the surface, and the lowering of the ground-water. The increase was probably several fold.

A complementary result of the increase of the land was obviously a reduction of the oceanic area and, particularly, a reduction of the shallow-water portion which had been the chief habitat of the limestone-forming life. From an area of perhaps 20,000,000 or 30,000,000 square miles in the early Carboniferous, the epicontinental seas were probably reduced to 10,000,000 or 15,000,000 square miles in the Permian, perhaps even to 5,000,000 square miles at the extreme stage of the Permian emergence. So great a reduction seriously curtailed the deposition of epicontinental organic beds, and markedly increased the deposition of clastic beds, and this was attended by other consequences now to be noted.

carbon dioxide in it is very many times greater than the carbon dioxide of the present atmosphere, and probably several times as great as the carbon dioxide of the atmosphere and the ocean combined. The calcium monocarbonate of the present ocean, by estimate, would make a stratum of limestone about ½ foot thick over the earth's surface, or about 4 feet over one half the present land area. The "loose" carbon dioxide united with this calcium monocarbonate to form bicarbonate, together with all the free carbon dioxide in the ocean, might, by liberal estimate, add 85% to this, if united with calcium to form limestone. The Subcarboniferous limestone mounts up in places to 2500 feet and more in thickness, and has a wide distribution on the land, and an unknown distribution beneath the sea. Without doubt we are accustomed to overestimate the mass of such formations, because we dwell upon their maximum, rather than their average or minimum thicknesses, and upon their known distribution in terms of our observational standards, rather than their proportions to the great unknown area of the globe; but yet from the data at hand, it seems inconsistent to assign the Subcarboniferous limestone a mass that is not much greater than the seven and a half feet for an area equal to half the present land, which is all that the present carbon dioxide of air and ocean could produce, if so converted. If we consider what a possible atmosphere and ocean richer in carbon dioxide might do, it seems idle to look to the atmosphere as even a possibly competent reservoir, consistently with the life that existed; for the carbon dioxide of the present atmosphere, if used up in making limestone, would form a layer of about one thirtieth of an inch thick only, over the globe. To form a layer one foot thick it would have to be increased 360 fold, which would surely imperil active, air-breathing life, unless it were different from similar present life.

The ocean under certain conditions has much greater competency to hold carbon dioxide, and, what is of prime importance, *to hold it in a condition harmless to animal life.* The carbonates of the present ocean, reckoned simply as monocarbonates, hold about 30 times the carbon dioxide of the atmosphere. To this is added a less amount in "loose" combination, to render them bicarbonates, and an additional quantity held by solution simply. Together, these may be roundly placed at 25 times that of the present atmosphere, giving in all 55 times the present content of the atmosphere. These are merely round figures, roughly approximate. Present data do not permit a close estimate of the "loose" and free carbon dioxide of the ocean.

The present ocean, however, is not saturated in calcium bicarbonate, for while the specific gravity of the sea ranges from 1.025 to 1.028, calcium carbonate is not precipitated appreciably until concentration by evaporation reaches 1.05, according to the careful investigations of Usiglio.[1] With the existing temperatures, it would be possible for the ocean to carry an additional amount of carbon dioxide in the form of bicarbonates,—precisely how much has not been experimentally determined. The higher temperature of the Subcarboniferous ocean would have been adverse; but it is probable that considerably more than 55 equivalents of the present atmospheric carbon dioxide might have been held

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[1] Enc. Brit. Art. Sea Water, p. 229.

ocean if it were as nearly saturated as was possible, and that withou
y affecting the animal life. It cannot of course be affirmed that th
case; indeed the probabilities are against it for reasons that will soo

But, to make the most of this resource, let it be supposed that, at tl
of the Mississippian period, the ocean contained, by virtue of i
tes, 60 to 80 equivalents of the present atmospheric carbon dioxid
iis would fall far short of furnishing all the carbon dioxide locked u
imestones of the period. It would, however, make a large contributio
requisite amount, and thereby help appreciably to solve the problen
! *it be assumed that the carbonates were removed from the ocean in tl*
f the period by consumption in limestone formation.

d this have taken place? The conditions for the extraction of calciu
te by lime-secreting organisms were especially favorable. The ma
eriod (Fig. 228) indicates that, aside from the continental shelves, abou
0 square miles of the continental area of North America were, by est
ubmerged, or more than half the present land area of North Americ
ncroachments are known to have taken place on other continents, and
estimate of submergence of one half the present land area is probabl
neighborhood of the truth. If the submerged continental area for th
placed at 20,000,000 square miles, in addition to the 10,000,000 of th
n now submerged, it gives a vast tract of water peculiarly suited to b
itat of lime-secreting life. When it is borne in mind that nearly the whol
secretion of lime takes place in the upper few hundred feet of the sea
ugh the agency of pelagic life whose habitat would be 10% greater tha
d (2) by epicontinental life whose habitat would be 200% greater tha
e potentiality of the geographic change may be realized. It is furthe
oted that the warm temperature of the times not only favored an abun
f lime-secreting life, but favored the process of lime-secretion itself, fo
erved that the animals of the warm seas secrete more lime, on the aver
n the same types in cold seas.

he other hand, it is to be noted that the supply of carbonates fron
l area was reduced in proportion as the sea was extended, and th
at remained unsubmerged was probably low, and had previousl
ch leached during the base-leveling processes. Hence the land water
ed the earth but feebly, from lack of head, and from hindrance b
p mantle of residuary earth that presumably covered the low lands
carbonation and leaching of the lands was therefore relatively feeble
s were therefore much less rapidly supplied with calcium carbonate than
ds when the lands were broader and higher, and the penetration of the
waters deeper and more active. The period therefore presented con-
avorable for the extraction of lime from the ocean waters, and unfavor-
renewing the supply. Under these conditions, unless there be offsetting
not now recognized, it may be assumed that the carbonates of the sea
adually reduced.

e the chemical relations involved are very complex and have not been much elucidated by direct experimentation as yet, and while the reactions are very difficult to anticipate theoretically, it seems permissible, in the present state of knowledge, to suppose that this process might go forward until the carbonates of the ocean were well nigh or quite exhausted. Even if completely exhausted, the calcium necessary for organic life could probably be supplied by the calcium sulphate, which is roundly ten times as abundant as the carbonate in the present ocean. Indeed, it has sometimes been urged that it is the calcium sulphate that is actually used by life, instead of the carbonate, but this does not appear to be sufficiently supported by experimental determinations. If calcium sulphate is converted by organisms into the calcium carbonate of their shells, skeletons, etc., the sulphuric acid set free probably unites with the bases of the carbonates of the water—except so far as converted into sulphides and deposited as such—and sets their carbonic acid free, so that the ultimate result of the reaction is much the same whether the organisms use calcium carbonate directly or calcium sulphate. This supposed depletion of the oceanic carbonates, even if it began with an ocean fully saturated by them and ended with complete exhaustion, would only *help* to solve the problem of the supply of carbon dioxide for the great limestone formations of the period, though the help would seem to be very important. But the depletion of the ocean content was probably a very radical feature in the atmospheric problem, to which this discussion is preliminary.

The rest of the solution of the problem of an adequate source for the carbon dioxide of the Subcarboniferous limestones is probably found in two other quarters. The limestone of the period was certainly not all original, in the sense of having been formed from the silicates of the crystalline rocks. A notable part of it was derived from the exposed portions of limestones previously formed. A comparison of the map of the period (Fig. 228) with the maps of previous periods (Figs. 95, 129, 174, 195, etc.), shows that not a little of the exposed land was formed of the older Paleozoic sediments, among which limestones were a notable element. Probably the lime in the previous sediments was not greater per unit area, on the average, than in the crystalline rocks, since the sediments were derived from the crystalline rocks. It was perhaps somewhat less, since there was some loss of lime to the ocean; but it was probably more readily removed. This removal involved the combination of a portion of the free carbon dioxide of the air with the limestone to form bicarbonate, which was thus dissolved and carried down to the sea. Thus a portion of the carbon dioxide was temporarily locked up, but when the lime was secreted by the sea organisms, this second equivalent of the carbon dioxide was set free, and was subject to diffusion into the atmosphere, where it was available for a repetition of the process. A comparatively limited amount of free carbon dioxide might thus serve, in time, as the carrier of a large amount of carbonate from the land to the sea. It is difficult to estimate the portion of the Subcarboniferous limestone which was thus derived from previous limestones, and the portion which was added by the original carbonation of the silicates of crystalline rocks, for the data are very inadequate.

remaining source of carbon dioxide was found in volcanic emanations
interior of the earth, and in the unknown supplies that came from cosmic

he foregoing sources combined may not improbably have been compe-
furnish not only the carbon dioxide required for the formation of the
e, but also for such other carbonate and carbonaceous deposits as took
The feature of most note is the function assigned to the carbonates
on dioxide of the ocean, which, by being depleted during stages of great
sgression, meet the exceptional demands of the great limestone for-
that characterize such periods, while at the same time, as the result of
ey leave the atmospheric-oceanic supply of carbon dioxide in a critical
reduction.

part played by coal-formation.—If the exceptional carbonic demands
reat Subcarboniferous limestone formation be met thus, in part, by deple-
ocean of its store of carbonates and carbon dioxide, the close of the
vould have found this resource exhausted, and unavailable for meeting
eptional demands during the following period; but it has been noted
re was an extensive withdrawal of the sea, in America at least, between
carboniferous and Carboniferous periods. Much erosion and decom-
must have taken place to give the cherts and quartzose material of the
e grit and equivalent formations. So great thicknesses of chert as occur
points imply the solution of much limestone, and this in turn implies
pplies of calcium carbonate carried to the ocean during the erosion inter-
ile the mere fact that the ocean was extensively withdrawn, and lime-
g life restricted, implies a reduction of the drafts made upon its calcium
te for limestone formation. To make this reasoning altogether firm, the
ns in North America must, of course, have been representative of the
t large. In the aggregate, this is fairly warranted, but not conclusively
by present evidence. It may, however, be assumed tentatively that
e main deposits of coal and limestone began in the Carboniferous period,
an had become, in some measure, re-enriched in carbonates and loose
dioxide. During that period there were considerable limestone deposits,
these were not equal to those of the preceding period; and there were
ge accumulations of coal and other carbonaceous materials which made
lrafts on the supplies of carbon dioxide. Here again, the data for a
al estimate are very imperfect. The productive coal fields of this age
h America are estimated to cover 265,000 square miles. North America
s about one seventh of the continental surface of the globe, but has rela-
nore coal of this age than other continents. For a rough approximation,
le may be put at two or three times that of North America. If the impure
nd other carbonaceous matter be included, an average thickness of 25
et for the whole area may be assumed, without pretension to accuracy.
bon dioxide of the present atmosphere, if reduced to pure coal, would
layer about 1 foot thick over an area of 500,000 square miles, or about
s thick over an area of 800,000 square miles. If there were no other

demands than those of the coal deposits, these might apparently be met by drawing on the stores of carbon dioxide in the air and ocean, without supposing these supplies to have been very unusual. To meet the concurrent demand of limestone formation, it may be supposed that the oceanic supply of calcium carbonate was again greatly reduced. It is possible that the volcanic and cosmic contributions during the period were more than usual, but there is little clear evidence of it. Considerable volcanic activity is indicated by the igneous rock of the series in certain regions, but it is not extraordinary, and no very general prevalence is indicated. The more probable view appears to be that the carbonates and carbon dioxide of the ocean were again reduced to a low state, and that this was the condition when the deformative movements brought other powerful agencies into action.

The enrichment of the air in oxygen.—The extraction of carbon from carbon dioxide to form coal set free the associated two equivalents of oxygen, which contributed to the enrichment of the atmosphere in that vital element. While some oxidation was in progress during the period, the low elevation of the lands, and their limited area presented conditions less favorable than usual for oxidation. The presumption is therefore that oxygen accumulated, and that the Permian period inherited from the Carboniferous an atmosphere unusually rich in this vital constituent. This inference appears to be supported by the exceptional prevalence of highly oxygenated red deposits in the Permian and Triassic periods, and this is perhaps their sufficient explanation, when taken in connection with the climatic conditions of those periods.

The relations of equilibrium between the carbon dioxide of the air and that of the ocean.—To realize how it is possible for the atmosphere to vary in its content of carbon dioxide through only such moderate ranges as were compatible with active air-breathing life and yet be the medium through which the ocean yielded such large amounts of carbon dioxide as were demanded for the exceptional limestone and coal formations (over and above what the volcanos and cosmic sources can be presumed to have supplied during these times of exceptional demand), it is necessary to recognize that the carbon dioxide of the atmosphere is in a certain kind of equilibrium with the carbon dioxide of the ocean. This relation is peculiar and intricate, and the precise conditions and ratios of equilibrium are as yet but imperfectly determined. It involves a complex series of interactions between (1) anhydrous carbon dioxide (carbonic anhydride, CO_2), (2) carbonic acid (H_2CO_3), (3) calcium and other bicarbonates ($Ca(HCO_3)_2$, etc.), and (4) calcium and other monocarbonates $CaCO_3$, etc.). In the air there are carbonic anhydride and carbonic acid, and in the ocean, carbon dioxide, carbonic acid, calcium and other bicarbonates, and calcium and other monocarbonates. Some of these were merely mixtures whose distribution was controlled by diffusion and mechanical stirring. Others were dissolved and held by the force of solution, and others still were united chemically and held by chemical forces of different strengths. For the present purposes, it may suffice to note that a reduction of the carbon dioxide of the atmosphere calls forth carbon dioxide from the ocean to make up part of the loss, and bring the two into

state of equilibrium.[1] The equalizing supply doubtless comes primai
he free carbon dioxide or carbonic acid of the ocean, but the reduct
these thereby suffer causes the water to absorb some of the feebly co
carbon dioxide of the bicarbonates, while it is temporarily dissociated, tl
ng the bicarbonates to monocarbonates. In the case of calcium carb
is tends toward precipitation because of its slight solubility. In the opin
e chemists, this process may go so far, if the atmospheric carbon diox
inually removed, as to call forth all the loose carbon dioxide of the bic
s of the ocean, and reduce them to monocarbonates, the calcium moı
ate being precipitated, which involves the proposition that all the bic
s of the ocean are held there practically by the carbon dioxide
r. Without accepting or rejecting this extreme proposition until expe
have gone farther and become more consistent, the more conservati
ation that there is an interchange in the direction of equilibrium m
ognized as an important working factor.

influence of the rate of diffusion.—But it is necessary to take care
f the qualifying conditions and retarding agencies. The re-establishme
ate of equilibrium after it has been disturbed is dependent on diffusi
mechanical mixture. If, for example, the air were robbed of one h
bon dioxide, the ocean having, we will assume, 25 times as much, eith
ple solution or in loose combination as the second equivalent of the bica
s, and remaining perfectly quiescent, the ocean would, by theory, ultimate
p enough carbon dioxide to make good about $\frac{25}{26}$ of the air's loss, and
uilibrium would be instituted. To reduce the carbon dioxide of the a
lf permanently, about one half of the great store in the ocean must

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e important conception of equilibrium was long since entertained by Schlœsi
imple theoretical application to the existing status (Sur la constance de
ion d'acide carbonique dans l'air, Comp. Rend., 1880, t. 90, p. 1410), a
rded the ocean as a regulating reservoir, so to speak, restraining the fluctu
f the carbon dioxide of the air. This was a very valuable contribution, b
ecular application to geological problems, it must be recognized that all t
are subject to change and, with them, *the basis of equilibrium itself*, and th
ults are qualified by rates of diffusion, areas of contact, temperatures, a
elements. (See The influence of great epochs of limestone formation
stitution of the atmosphere, Chamberlin, Jour. Geol., Vol. VI, pp. 609–621, 18
p of hypotheses bearing on climatic changes, Jour. Geol., Vol. V, pp. 653–6
An attempt to frame a working hypothesis of the cause of glacial perio
atmospheric basis, Jour. Geol., Vol. VII, pp. 545–584, 667–685, 757–787, 18
nd also Tolman, The carbon dioxide of the ocean and its relation to the carb
of the atmosphere, Jour. Geol., Vol. VII, pp. 585–616, 1899.)

gh has recently made valuable contributions to Schlœsing's conception, b
adequate recognition of the qualifying and secular factors of the proble
tension of carbonic acid in natural waters and especially in the sea, Vol. XX
p. 334–405, Meddelelser om Gronland, and The abnormal CO_2-percentage
in Greenland and the general relations between atmospheric and oceanic ca
cid. Idem, pp. 409–436.)

removed, as well as half of that in the air; hence the slowness of permanent changes in the carbon dioxide of the air. But this theoretical conclusion is qualified by the rates of diffusion of carbon dioxide in sea-water. The rate of this diffusion has not been experimentally determined, but supposing it to be as high as other rates of diffusion that have been determined, it would require millions of years for any notable percentage of the above restorative action to take place, and the completion, or even closely approximate completion, of the whole process would apparently require more than the lapse of known geologic history.[1] This, be it noted, is on the assumption of quiescent waters when diffusion acts alone.

The influence of agitation and circulation.—Agitation, combined with diffusion, accelerates the process, indeed, its efficiency is practically dependent on the surface agitation and on the circulation of the ocean. The agitation of the ocean is quite superficial, and the more conspicuous part of its circulation is also superficial. Now it is in this superficial, sunlit part that nearly all the plants of the ocean live, feeding upon carbon dioxide and setting oxygen free. This is partly, but not wholly offset, by the animal life in the same horizon, for observation shows that it is relatively low in carbon dioxide and high in oxygen. It is this inherently impoverished layer, especially affected by organic action, that is subject to agitation in contact with the air. This layer intervenes between the great bodies of the air and of the ocean that are but slightly affected by local organic action and between which the chief equilibrium exchange must take place, if it takes place at all. The diffusion which directly affects the body of the ocean is that between the superficial layer impoverished by plant action, and the great mass of waters below. If the matter were pursued into detail, it would be found that the state of carbonation of the superficial part of the ocean, and its interchange of carbon dioxide with the air above and the great body of the ocean below, are subject to much variation in different parts and different seasons; but upon this we cannot here enter.

That portion of the oceanic circulation which is most concerned in the carbonic equilibration of the air and ocean, is the deep circulation which now is initiated in the polar regions by reason of their low temperature. As this is a function of temperature, it brings us to the second qualification of the tendency to equilibrium.

The influence of temperature.—The coefficient of absorption of carbon dioxide in sea-water increases rapidly as the temperature is lowered, the rate being doubled for about 21° C., lowering[2] in the vicinity of 0° C. At present, the temperature of sea-water, in passing from the equatorial regions, where it rises from the depths, in the abysmal circulation, to the polar regions, where it descends, experiences a reduction of several degrees more than 21° C., and hence, if the air and ocean were in carbonic equilibrium at the equator, they would be far out

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[1] This statement is based on a mathematical inspection by A. C. Lunn. For an analogous application of the rate of diffusion to lavas see Becker, Am. Jour. Sci. III, 1897, pp. 27–29.

[2] Krogh, loc. cit. pp. 363–365.

ıilibrium in the polar regions. In such a case, in passing from the (
other, the surface waters must be absorbing carbon dioxide, as long :
ized by Dittmar and others. Relative to the average state of equilibri
e whole contact surface, whatever that may be, the equatorial port
be more highly charged, other things being equal, and the polar port
ighly charged. If the average state at the surface is near equilibri
juatorial portion is probably emitting carbon dioxide and the polar p
bsorbing it. This is probably the actual condition now and perhaps l
generally in those geologic ages in which the climatic states were similar
of the present. It may be accepted as a general proposition that,
urse of the abysmal circulation, essentially all oceanic waters pass throu
ısorbing stage in the polar regions and the emission stage in the equatoi
s, and that the adjustments of equilibrium for the great mass of the oce
pendent on this slow circulation, whose period may equal a glacial epo
imating it, the more active wind-actuated circulation of the surface m
ently be set aside, in the main, as having little to do with the abysn
ıtion. It has recently been shown in the investigation of small lak
depths rarely reach 200 feet, that the wind-driven circulation has lit
on the basal waters, but develops a surprisingly shallow superficial zc
own. The waters below this are sometimes so far unaërated, or so charg
ıoxious gases, as to be offensive and inhospitable to life.[1] The tempe
of the deeper waters of lakes, however, show that there is a seasonal desce
l waters analogous to the abysmal circulation of the ocean, but essentia
endent of the eolian circulation. (For the hypothetical reversal of circulatic
ı. 432–446, Vol. III.) The discussion here will proceed on the suppositi
he present deep-sea circulation was persistent.

e influence of secular temperature changes.—If the polar temperatures
ild stage previous to the Permian period averaged about 20° C., as t
ems to imply, the abysmal waters would become carbonated on the ba
ır absorption at 20° C. If, other conditions remaining the same, the po
rature at the time of the Permian glaciation was reduced somewhat bel
esent temperature, the basis of equilibrium must have shifted to absorpti
C. to −4° C., or to an absorption ratio about double its previous one.

g the adjustment to the new basis of equilibrium, corresponding dra
e atmospheric carbon dioxide are to be inferred. It follows from the
erations that at a time when the polar temperatures were being lower
he basis of equilibrium was being changed adversely to the atmosphe
ıt of carbon dioxide, the latter was ill conditioned for meeting exceptio
ıds made upon it from other sources.

hen this critical state, arising from the very conditions of equilibrium itse
en in connection with the depleted state of the oceanic carbon dioxi
g from previous exceptional extraction to form coal and limestone, it w
parent that the Permian deformation was liable to produce unusual effec

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[1] E. A. Birge, Wis. Geol. and Nat. Hist. Surv.

With these conditioning influences and liabilities in mind, we may resume the sequences of the Permian deformation.

1. **Interruption of the water-heating system.**—The first effect, as already noted, must have been a serious interruption of the free polar circulation that had previously prevailed, and which has long been confidently regarded as one of the greatest of the agencies that maintained the previous mild temperature in those regions. In the Southern Hemisphere, the distribution of life furnishes special reasons for believing that the land was appreciably more extensive, and more completely connected, than it is at the present day, and geologists, quite without reference to any climatic effects, have postulated such connections. A migrating tract for land faunas and floras between India, Australia, South Africa, and South America seems to be requisite, and even if this were supplied in the most conservative way, it must have seriously interrupted the high-latitude circulation of that hemisphere. The constraint of the oceanic circulation in both hemispheres must have greatly reduced the temperature of the polar regions. This quite certainly led to greater differences of temperature between the air columns of different latitudes, and this must have intensified the vertical circulation of the atmosphere, and accelerated the loss of heat from the surface.

2. **Extension of continental climates.**—A second effect of the increase of the land areas was an increase of the continental elements of the climates, and a strengthening of the atmospheric circulation between land and sea. This further intensified the vertical circulation and accelerated the loss of surface heat. The mountains and other reliefs introduced by the deformation still further aided in checking horizontal circulation and intensifying vertical circulation.

3. **Reduction of humidity.**—A third effect was a reduction of the average moisture of the atmosphere. This is not only a firm theoretical deduction from the increase of the land area and the reduction of the water area, but is depositionally indicated by the remarkable prevalence of salt and gypsum deposits and of red beds. There is no question that the vapor of water plays a large part in the retention of the heat radiated from the earth, and so acts as a thermal blanket, and hence the reduction of this blanket led to less retention of the solar heat, and hence to a lower temperature. As this was truer of the land areas than of the oceanic, the climate must have been differentiated geographically into intensities of dryness and humidity, and of heat and cold. These must further have involved an increase of convective currents, and hence an additional loss of heat.

4. **Depletion of the heat-absorbing constituents of the atmosphere.**—A fourth effect is assigned to a change in the constitution of the atmosphere affecting especially its heat-absorbing constitutents. The reduction of moisture was a part of this change, but reference is here made to the more permanent constituents, particularly carbon dioxide. The increased area of the land, and its increased elevation, gave increased contact between the atmosphere and the rocks of the earth susceptible of carbonation and oxidation, as already indicated. As a result, the atmosphere lost carbon dioxide and oxygen at a more rapid rate than in the previous period. Oxygen plays some part in the thermal blanketing

earth, but any change it is likely to have undergone was probably
ently large to make it needful to dwell upon it here. But if the carl
le in the air and in the ocean was in the critical state of reduction we h
ed from previous losses, and was being absorbed by the ocean on acco
cooling experienced from the above changes of condition, the accelera
nation induced by the deformation may well have made serious inro
it. It is accordingly inferred that its quantity was reduced appreciat
nat the earth was thereby deprived of some large part of the thermal blank
hich it had previously effected.

e vicarious action of carbon dioxide.—Before considering the amount
eduction, let it be noted that, in so far as it reduced the temperature, *it*
the moisture in the atmosphere, for this is immediately dependent u
rature, and any agency which reduces the temperature reduces the moistu
ence reduces the thermal effects due to moisture. Probably this second
of a loss of carbon dioxide is greater than its primary effect. To real
t is important to recognize the fundamental difference between the re
permanent constituents of the atmosphere, such as nitrogen and oxyg
uch an exceedingly dependent and fluctuating one as the vapor of wat
mperature effect arising from moisture seriously affects the amount
n, nitrogen, or carbon dioxide in the air, while any reduction of these wh
es reduction of temperature, effectually reduces the water-vapor. Wh
uction of temperature does not immediately reduce the carbon dioxi
ls indirectly to its absorption in the ocean, and so a reduction of eit
dioxide or water-vapor reduces the other, and their mutual react
ifies their common temperature effect. Saturation being assumed,
tical amount of water varies with the temperature, but unequally.
cinity of 0° C., the amount of vapor varies roughly about 7% for ev
Centigrade, when computed from one degree to another, or, round
apor is about doubled or halved for every temperature change of 10°
e amount of vapor in the air at −30° C., when completely saturated, ab
the normal amount of carbon dioxide in the air. The air is, howev
saturated with moisture. While, therefore, the amount of vapor in
on the whole, much greater than the carbon dioxide, there are consid
igh-latitude areas at the ground surface, in addition to the whole up
in which the carbon dioxide exceeds the vapor of water.

e thermal functions of the atmospheric constituents.—Although not a lit
mental work has been done on the competency of the atmosphe
to absorb heat, it has not furnished an adequate basis for the satisf
liscussion of their relative serviceability in maintaining the temperat
earth's surface. In part this has been due to the great difficulties of ac
determining the absorbent effects of the chief thermal rays, which ha
vave-lengths (.4μ to 30μ) and are invisible. These long wave-lengths

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or exact data, see Landolt and Börnstern's Physikalisch-Chemische Tabell
ans' Physico-Chemical Tables.

almost the only ones that are radiated from the earth at its ordinary temperatures, and it is the retention of these upon which the surface temperature of the earth chiefly depends. It is only by the masterly work of Langley and others, that instrumental devices have been invented capable of exploring the lower end of the spectrum which is formed of these rays, and even these devices have not yet reached a sufficient degree of refinement to completely separate the individual effects of the gases. There is a further difficulty in the feebleness of the rays emanating from bodies at the temperature of the earth's surface. Higher temperatures, as that of boiling water, have therefore usually been employed in experiments; but as the proportion of short wave-lengths increases with the temperature, most of the experiments are not directly applicable to the problem in hand, and, besides, the results are not very consistent at best.[1] It is known that the same amount of moisture absorbs more radiation when near saturation than when much below it, which is perhaps due to a larger proportion of carbonic acid (H_2CO_3) in proportion to carbonic anhydride and water-vapor (CO_2+H_2O). The thermal efficiency of carbonic acid proper (H_2CO_3) has not been determined. For the present it is therefore necessary to accept rude approximations only.

Two modes of absorption of radiation are recognized, general and selective. When a molecule takes up those vibrations which it itself gives forth, when agitated, the absorption is selective. Gas composed of a single kind of molecules takes up the vibrations proper to it, as the string of a musical instrument takes up and reproduces the vibrations to which it is attuned. Other vibrations, for the greater part, pass through it without interference, but not wholly so. In partial and irregular ways, not fully understood, some parts of the vibrations of other lengths are absorbed. This incidental or irregular action constitutes general absorption. The nitrogen of the air does not absorb selectively much of the radiation of the sun or of the earth's surface, both of which pass through it with little modification, but not wholly without general absorption. Oxygen absorbs a larger number of known wave-lengths in the visible spectrum, but the amount of heat energy involved is not very large. Oxygen does not appear to absorb the long wave-lengths of the heat radiated from the earth to any notable extent. Carbon dioxide, on the other hand, absorbs certain bands of long wave-length rays whose energy is large. Arrhenius has lately determined experimentally the absorptive capacity of carbon dioxide for rays emitted by a body at 15° C., about the average temperature of the earth's surface, as follows:[2]

Amount of absorption...............	1%	2%	5%	10%	15%	20%	25%	30%
Amount of CO_2 traversed in cm. (at 15° C. and 760 mm. air pressure)...	0.6	1.3	5	20.7	60	142	300	580

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[1] Paschen, Wied. Annalen, Vol. LIII, 1894; Angström, Ann. Phys. u. Chem. 3, 1900; Rubens and Aschkinass, Ann. Phys. u. Chem., 64, 1898; Arrhenius, Kosmische Physik, II, 1903.

[2] Kosmische Physik, II, p. 503. 1903.

ese results are subject to some qualification because certain of the exp
l conditions differed somewhat from those of the atmosphere, but tl
to be the nearest approach to natural conditions yet attained in exp
tion. From the results, Arrhenius estimates that about 28% of the ear
ion is absorbed (oblique transmission included), and that the carbon diox
atmosphere influences the earth's temperature to the extent of 14.5
·öm has estimated the absorption of carbon dioxide as at best only 1
earth's radiation.[1] From the percentage curves of Rubens and Aschkin
d to an energy curve determined by Ångström, we deduce about 8% abso
y carbon dioxide,[2] but the deduction is subject to several rather seri
s of probable error.

om Ångström's experiments, the following absorption values have b
ed [3] for water-vapor:

nt of absorption.	5%	10%	15%	20%	2
nt of vapor traversed (measured as water in cm.)	0.3	0.85	2.1	4.2	6.

ving to the differences of temperature, of the quantities used, of the degr
npression, and of other conditions involved in the experiments, on
and, and to the lack of adequate data as to the average amount and
ion of moisture in the air, on the other, it is impracticable at present
the relative values of the thermal absorption of the water-vapor
carbon dioxide of the present atmosphere, respectively, but it seems cl
he efficiency of the vapor is several times that of the dioxide.

e time of retention.—There is a defect in all the experimental work
t does not show the secondary or retentional effects of added quanti
gases. If a given quantity of gas absorbs 90% of all the radiation wh
gas can absorb by selective action, the addition of a second quantity
amount could only selectively absorb, *at first hand*, its proper proport
10% that had escaped previous absorption, but it would absorb *secondar*
adiated from the previously absorbed 90%, and delay its escape, as
iate a portion of it back toward its source. It is not the simple absorpt
it that determines the climatic effect, but the time of its retention, or,
words, the number of secondary absorptions and radiations. A gi
ity of vibratory energy retained ten seconds within the basal strat
air by a series of re-absorptions and re-radiations, is as effective, clima
s ten times the amount retained one second. While increase in the amo
as does not proportionately increase the percentage of primary absorpt
vibrations of its appropriate wave-lengths, it increases about prop
ely the number of times these are absorbed and re-radiated before t
escape.

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[1] Ann. Phys. u. Chem., 1900, p. 324.
[2] Ann. Phys. u. Chem., 1898, p. 598.
[3] Kosmische Physik, II, p. 505.

Primary independence in selective action.—It is important to note that *in selective action each gas absorbs its own wave-lengths, and these only.* No matter what its quantity or its relative competency, it cannot do the selective work of another gas. This is not experimentally demonstrable in the dark spectrum, from lack of sufficiently refined means of analysis, but in the visible spectrum the absorption lines of each substance differ from those of all other substances, so far as perfect determinations can be made, and there is no reasonable ground to doubt that this holds true in the dark spectrum also. Where bands appear to overlap, they are to be interpreted as intermingled groups of lines which are individually distinct. It is an error, therefore, to suppose, as some seem to have done, that any amount of water-vapor can replace, or interfere with, the absorption by carbon dioxide. Of the vibrations of various wave-lengths sent forth by the earth, a certain set are absorbed by the molecules of water, a certain other set by the molecules of carbon dioxide, some few others by the other gases, and the rest escape, except as caught by dust, clouds, general absorption, etc. This relates to primary action, and to a certain portion of the secondary action.

After a molecule of carbon dioxide has absorbed its appropriate radiation, and increased its vibratory energy correspondingly, it radiates wave-lengths of its own kind, which can be taken up by other molecules of carbon dioxide, but not by the molecules of other gases. The number of re-absorptions and re-radiations of such wave-lengths is dependent upon the number of dioxide molecules that lie in the paths of such re-radiations, which are in all directions, some being, of course, back toward the earth, or laterally, where they will be re-absorbed in adjacent parts of the atmosphere. The same is true, of course, of all the other molecules relative to vibrations of their own wave-lengths. Thus there is measurably perpetuated independence of action.

Thermal transference by molecular contact.—While, however, the preceding action is in progress, each molecule is colliding with its neighbor molecules many million times per second, and communicates some of its heat energy by such contact. The molecules thus heated radiate wave-lengths of their own order, and *these* may be absorbed by molecules of the same kind. Thus vibrations may be transformed so as to be absorbed by all the constituents of the air in succession, and their retention within the air be greatly prolonged, because of the great mass of some of these constituents.

The critical point is obviously the first absorption that starts the transfer by impact. If there is no constituent to take up the vibration from the other, it escapes. but if it is once taken up by a molecule, it may be transferred a multitude of times before it escapes.

Just what is the measure of the efficiency of carbon dioxide in contributing to the temperature of the earth is not yet determined, and so the influences of changes in its amount on the climate are as yet undeterminable, but as one of the factors in the complex of agencies, it seems to require a place in our working hypotheses.

:al thermal efficiency of the atmosphere.—It seems worth while in thi:
:tion to try to estimate the total agency of the atmosphere in preservin
mperature of the globe. The earth and moon are at practically the sam
distance from the sun, and would doubtless have practically the same tem
re if the earth had no atmosphere or ocean. (The ocean is theoreticall
'ative from the atmosphere.) If the present mean temperature of the earth'
be taken at 15° C., the absolute temperature is −288° C. As the resul
ecent elaborate study, Very estimates the temperature of the moon a
lday to be 97° C.[1] Several other astronomers have thought that the moon'
y temperature did not rise much above the freezing-point. The rang
petent opinions may then be limited by the boiling- and freezing-point
nd 273° absolute. It is agreed by all that the lowest night temperatur
t be far from absolute zero. Allowing this, however, to be 55° absolut
erage temperature of the moon on the higher estimate is 214° and, o
wer, 164° absolute. The difference between these, respectively, and th
temperature of the earth, 288°, is 74° and 124°, of which the mean is 99
there is a rather large element of uncertainty in the estimates of the moon
rature, their mean gives countenance to the belief that the efficiency
rth's atmosphere, as a thermal blanket, may be in the neighborhood
%.

the mean temperature of the earth in the Carboniferous period be place
C., it will doubtless be about high enough, for that is a tropical temper
nd if the mean temperature of the glacial stages of the Permian be place
C., this will perhaps be low enough. The range between these, 15° C
, on the basis above deduced, make the change from the one to the oth
15% of the total efficiency of the atmosphere. When allowance is mad
effects of increased vertical circulation, it does not seem that it is taxin
signed changes in the water-vapor and carbon dioxide too severely to mak
responsible for the remaining portion of the 15% of the whole therm
tency of the atmosphere.

IV. The Localization of the Glaciation.

e remarkable distribution of the Permian glaciation is the most puzzlin
e of the whole problem. The localization of the recent Pleistocene gl
was also peculiar, as will be seen, but still it was measurably circum
as we should expect any general glaciation to be. Among the explana
offered for this later puzzle is one which connects it with the areas of *pe*
t low atmospheric pressure in the North Atlantic and North Pacific region
ich the present glaciations of Greenland and Alaska are located, and t
they apparently owe their exceptional development.

itative conception of the "fixed lows" and their relations to glaciation.–
ause of the prevailing low pressure and permanent cyclonic character c

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robable range of the temperature of the moon, Astrophys. Jour., VIII, 189
. See also the temperature of the moon, S. P. Langley, assisted by F. W. Ver
cad. Sci., I.

these areas is yet to be demonstrated, but one of the conceptions of their dynamics that seems to be warranted at present, seems also to be helpful in explaining peculiarly localized glaciation. In this conception, mechanical and vaporous energy are assigned a controlling value in determining the special configuration of the air movements, while thermal energy is placed in the background in a double sense. It is, of course, recognized that, at bottom, the chief agency in atmospheric circulation is unequal heating. Unequal distribution of moisture is also an original agency, since the superior kinetic energy of vapor, relative to its weight, renders the air column of which it forms a part lighter than if formed of dry air, other things being equal. This amounts to an appreciable agency. While the amount of its effect is dependent on the absolute amount of vapor present, its operative efficiency is dependent on the difference in its abundance in the different parts of the atmospheric province, precisely as in the case of heat. Starting from one or the other of these original sources, or from a combination of the two, circulation is inaugurated; but, when once under way, many secondary factors of a mechanical, rather than thermal or vaporous nature, are developed, and these appear to greatly influence the special configuration which the air movements and even air pressures actually assume. Some of these mechanical factors are closely derivative from the original thermal or vaporous energies, as the exceptional violence of squalls, tornadoes, etc., while some spring from the modifying effects of independent agencies, as the rotation of the earth, the configuration of the surface, the distribution of land and water, the ocean currents, etc.

Now, it is conceived that in a region where the agencies last named are specially influential, and the influence of differential temperature is not particularly strong, the mechanical factor and the vapor together may be dominant, and as they are fixed geographically, the cyclonic area also becomes fixed, instead of moving with the atmosphere, as do the more familiar cyclones. It is not intended, however, to imply that even these are not measurably dependent on derived mechanical energies. It is further conceived that in these fixed cyclonic "lows," the moist air of the great central tract is mechanically forced to rise *at a relatively low temperature* and the precipitation is hence favorable to glacial accumulation. In a more purely thermal cyclone, the relatively high degree of heat involved in *immediately* actuating the cyclonic movement is present to antagonize glacial accumulation. This conception is extended to the moving cyclones within the permanent cyclonic area, and perhaps even beyond. It is to be understood that this is not established meteorological doctrine. These are problems, like the rest of this complex of puzzles, yet awaiting final elucidation. The special point of application here lies (1) in the fact that this conception provides for precipitation with a minimum of heat by assigning mechanical energy and vaporous levity as the dominant actuating agencies, and (2) in that it gives a fixed location to the low-temperature precipitation that follows.

Probable geographic features of the glacial stage. If the land extensions and connections in the Southern Hemisphere in the Permian period be made as slight as biological data permit, they would probably at least consist of a con-

from India, *via* Australia and the old submerged land, to New Zealand,
ence to Antarctica, and through this to South America. Other and more
rly connections between India and South Africa, and between the latter
outh America, have usually been postulated. In the minimum case,
anic circulation must have been very different from the present, for the
quatorial currents from the Pacific that now flow through the East Indian
into the Indian Ocean must have been turned back into the Pacific, con-
ting its heat there. At the same time, two thirds of the cold waters flowing
the borders of Antarctica, which now largely pass south of New Zealand
e Southern Pacific, must have been arrested by the postulated New Zea-
ntarctican isthmus and turned northward into the Indian Ocean. The
esult was a concentration of warm water in the Pacific, and of cold water
Indian Ocean.

road Arctic tongue of sea is thought to have occupied eastern Russia and
n Turkestan about this time. It appears to have had an open polar mouth,
ulterior connections in the Arctic regions are unknown. So, too, its con-
ns toward the south and east are uncertain at the precise time of the gla-
It is not, however, beyond permissible hypothesis to suppose that
rctic embayment may have been occupied by a returning Arctic current
Labrador type. If so, this tended to extend the Arctic low temperature
rward in about the same longitude as the Antarctic movement.

hypothetical development of localized glacial conditions.—The postulated
of these configurations was the concentration of large portions of
lar currents in the longitude of the glacial areas, resulting in the intensi-
n of the atmospheric gradients on that side of the sphere, and leading to
uliar asymmetry in the atmospheric circulation. Hypothetically, this
into play, in an unusual degree, the derivative mechanical factors in the
tion, and led to the development of fixed cyclonic areas in exceptionally
titudes. The cold polar currents are assumed to have furnished to the
s of the fixed "lows," cool moist air, which, forced to rise rather by mechan-
ovement and aqueous kinetic action than by high temperature, gave *per-*
precipitation at sufficiently low temperatures to promote glaciation. Per-
clouds and fogs, habitual in such situations, are presumed to have shielded
lacial surface by their high reflecting powers, and to have become
tant auxiliary agencies.

ernative views. — The special problem of Permian glaciation has not
ped such voluminous discussion as has that of the Pleistocene period,
because its verity has only recently been established, and because the
ty of glacial students are not personally familiar with its phenomena.
nge of the earth's poles has naturally been suggested, since a shifting of
uth pole to the center of the Indian Ocean would relieve the problem of
st refractory element, the location of the glacial areas on the borders of
pical zone. Such a shifting, even if we ignore the extremely serious dy-
l difficulties involved, does little more than mitigate the problem of locali-
, for if the pole were placed equidistant from the three glacial centers in

India, Australia, and South Africa, it would be farther away from any one of them than is any present center of continental glaciation from the present poles. In most of the ancient periods, the polar regions do not seem to have been affected by glaciation, but rather to have been frequented by ferns, corals, figs, and magnolias. A general climatic stage verging toward glaciation and furnishing an appropiate climatic environment for a regional concentration of frozen precipitation, is prerequisite, and this is the primary problem.

Local elevation has been postulated, but the stratigraphic and other geologic evidences do not seem to support it. Marine beds are interstratified in the glacial series without evidences of extraordinary elevation and intensified erosion between their respective depositions. A case has been cited in which a bivalve was found standing on edge, as in life, in clay among glacial bowlders. Other evidences of iceberg deposition have been adduced, implying that the glaciers reached the sea.

The Crollian hypothesis[1] assigns this as well as other glaciations to a temporary increase in the ellipticity of the earth's orbit. If the fundamental conception is valid, ellipticity might be a cooperating agency, but, as already remarked, the general conditions that render any areal glaciation on lowlands possible would seem to be a prerequisite to its effective action. The hypothesis is virtually reducible to a change in the distribution of heat between summer and winter, the sum total of the heat remaining the same. In those periods in which the polar night was not fatal to ferns, figs, and magnolias, the elliptical variation could scarcely be effective.

Among the purely astronomical hypotheses, the variability of the sun's heat, which is supported by the recent observations of Langley[2] and Abbot, is the most substantial. Obviously, however, short-period variations in heat emission are inapplicable, as the glacial epochs can scarcely have been less in length than some few tens of thousands of years each; and the problem of localization, that thorn in the flesh of all hypotheses, is left untouched.

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[1] Climate and Time.

[2] The solar constant and related problems. Astrophys. Jour. 1903, pp. 89–99.

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